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Investigation and Feasibility Study to Replace Asphalt Roadway into Solare Roadway

Prepared by: Dllshad Mwani

Senior fellow and coordinator at MIRS

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By: Dilshad Mwani

Contact us

Email: Info@mirs.co

Official website: www.mirs.co

Tel: 00 (964)7701951736

00(90)5338601514

Facebook: https://www.facebook.com/mirs.english/

Twitter: https://twitter.com/MIRSEnglish

About Author :

He is an expert on Managing oil and gas sector, He has an M.A in Oil and Gas Management at Birmingham City University. He is also a senior fellow and Coordinator MIRS.

Abstract

Sustainability is critical in current engineering designs, especially in the area of pavement engineering, and is founded on having only limited resources while attempting to maximize designs for operation. To this end, developing infrastructure that can meet multiple needs is highly beneficial to society's will to live at our current standard of living.

One such task is the proposition to build roads that have been integrated with photovoltaic cells in order to supply a high performance driving surface while generating renewable electricity. This electricity could then be used by local infrastructure, adjacent buildings, or sold to the electrical grid. In order law to do this there are many challenges that necessitate to be overcome, as these roads cannot be built from traditional road surface materials, and a thorough analysis of many design aspects needs to be seen.

This report looks to determine, based on existing pavement materials research, how such a road panel can be manufactured and structured. Specific elements investigated include the design of each stratum of the solar road panel, how the panel can be integrated with photovoltaic electronics, how such a conception can be waterproofed, and how to optimise between solar capture area and structural unity.

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GLOSSARY

ENCLATURE

G	Solar irradiance
IM	Output current from the solar module
I	Output current from the solar cell
d	Piezoelectric charge constant
Isc	Short circuit current
Ns	Number of solar cells in series
T	Temperature
V	Voltage across the output terminal
T	T Mechanical stress

ACRONYM

AC	Alternating Current
DC	Direct Current
AADT	Annual Average Daily Traffic
BCU	Birmingham City University
STC	Standard Test Condition
VI	Voltage, Current product
TIC	Technology Innovation Centre
UK	United Kingdom
LED	Light Emitting Diode
TV	Television
US	United State
STC	Standard Test Conditions
LDV	Laser Doppler Vibrometer
HMA	Hot-Mix Asphalt
RPM	Reflective Pavement Markers.
VAS	Vehicle Activated Signs
SRI	Solar Roadways Incorporated
SBIR	Small Business Innovation Research
STTR	Small Business Technology Transfer Research
GAB	Graded Aggregate Base

Chapter 1

Introduction and Review of Literature

1.1 Introduction

Global warming has become one of the most complicated issues faced by the world in the present century and has resulted in a sharp change in the climate all over the world in recent years (J. K. Casper, 2010). The climate change has been observed via the instrumental temperature record, rising sea levels, and decreased snow cover in the Earth's northern hemisphere. These unwanted changes may be attributed to a significant amount of carbon dioxide released into the earth's atmosphere. The industrially developed nations are often made to take responsibility for these changes as they have been emitting the greenhouse gasses without any restriction starting from the days of the industrial revolution. Hence, united kingdom, in particular, is recognised as one of the industrially advanced in the world, has a duty to protect the natural environment and to reduce the emission of greenhouse gases (Houghton, 2009).

An increase in the use of renewable energy resources has been considered as one of the main solutions to reduce the global warming. Different types of renewable energy resources such as solar, wind, ocean and geothermal energy resources are available to employ. Among all these renewable energy resources, solar energy is the only resource available all over the world properly and distributed more constantly. Hence developing technologies to use this solar energy will be the most appropriate at these changeover times.

In order to sweep over the relatively low efficiency of the solar panels, significantly large amount of clear spaces are needed in the photovoltaic solar panel applications for the production of electricity to match the present energy demands. Nevertheless, availability of large open places is on the decline near the urban regions and hence the solar panels can simply be installed in distant regions, which may result in huge energy losses while transporting electricity. The low efficiency of the solar panels as well as the essential to deal with the transmission losses makes the usage of solar panels an unfeasible economical option to get electricity. In order to build the solar power a feasible economical option, open spaces that are available closer to the highly populated (high energy demand) areas must be placed.

Therefore, it is proposed that open spaces such as the roads, car park, bicycle lanes, pedestrian space etc. be utilised for this purpose. In order to use these open spaces for producing electricity using solar panels, recently, the concept of solar roadways has been introduced. The theory of solar roads has now developed as a strong contender where the solar energy collectors can be incorporated directly in the design of motorway infrastructure and the energy can be transferred directly through the available grids or sent to storage facilities for later use. So, the primary objective of this research is to investigate the feasibility of this unique idea keeping in mind the long term sustainability while giving importance to safety and performance. In an effort to find out the feasibility, the present study will consider important factors such as roadway surface material durability/performance,
Solar panel efficiency and various losses involved in this system as well as ways to overcome them (Laurie David & Cambria Gordo, 2007)

1.2 Rational

There are many advantages in following up the development of this technology, which is expected to revenue major contribution to the current global energy requirement. Hence, by using solar roadways, huge amount of carbon dioxide produced by the power plants can be reduced to a considerable level which can limit global warming. Also, the dependence on nuclear power plants can be reduced and the nuclear disasters like the one recently occurred in Japan can be avoided.

The electric vehicles produced now by various automobile manufacturers are meant for short range, i.e. they can only travel up to few hundred kilometres after which the batteries need recharging. With solar roadways, road side charging stations can be developed so that the electric cars can be recharged. Thus, the dependence on fuel can be reduced and hence the contribution to the greenhouse effect by automobiles can be reduced.

The solar roadway technology can also help the countries whose economy are largely affected by the price rise of oil.

This technology can also lead to the growth of new intelligent highway systems which consists of LEDs (Light-Emitting Diode) for painting the road lanes from beneath the open in order to get to the roads visible during the toughest driving conditions. Further usage of this ability can be used in developing temperature sensitive heating elements to prevent snow/ice accumulation during the extreme winter climates, and microprocessor boards for control and

communications. With this kind of agreement, the potential applications are numerous, and should this technology grow, these varieties of possibilities would be dateless. One of the primary limitations in employing this technology is in finding a suitable material that can substitute the glass cover on the solar panels. This material must have the desirable properties to withstand the load of vehicles moving over the panel while providing sufficient traction between the road surface and the wheels. Hence, a study is required for investigating the load carrying capability of the commercially available materials for the solar panel top cover. This study needs to be based on the streets as well as the deflection analysis, and a platform when developed may aid further development of a suitable panel cover for this application. The specific losses that are involved in this technology such as the fast moving shade effect due to the vehicles moving over the solar panels must also be identified and the effects must be addressed in the analysis. Other environmental and technological factors such as solar cell temperature and uncertainty in solar radiation that can act upon the solar panel output also need attention in an attempt to see the effects on overall power production. In order that this technology can be carried out in the near future, it is desirable that an auxiliary energy harvesting system be modernised for this application. The demand for such a system is seen in additional power production for compensating the various energy losses associated with the solar panel.
Besides its fundamental benefit as an environmentally attractive system, Solar Roadways boasts significant economic benefits. For one, Solar Roadways essentially "pay for themselves" in the long-run because they would provide vast amounts of electricity to homes and businesses across the nation.

Strengthening of glass. And also comparison between current roadway surface and Glass roadways will be carrying out in term of road traction, with the possible alternative solutions.

Nowadays, the solar technologies offered the most actual opportunities for generating renewable energy. Through this project evaluation and appraising of the most magnificent benefit would be applied. And also Comparison between current UK traditional asphalt roadway and the smart solar roadway would be carried out in relation to, cost, environmental cleaning and reducing carbon footprint. Finally, as regards to achieving renewable energy
From the sun, "**I'd put my money on the sun and solar energy. What a source of power! I hope we don't have to wait till oil and coal run out before we tackle that.**" (Thomas Edison 1938, Solar zone 2012)

1.3 Overall aims and specific objectives

The aim and objectives which have been designated as fundamental of the project are:

i. Aim:

- The fundamental aim of this project is to evaluate the feasibility and benefit of replacing asphalt roadways with the solar roadways.

ii. Objectives:

- To evaluate the literature relating to the current position of solar roadway technologies in the marketplace.
- To study the feasibility of implementing Solar Roadways in the UK roadways and car park.
- To study the result of fast moving shades over the solar panels of the solar roadway system
- To investigate the Power output variation due to the solar panel and environmental influence.
- To consider the characteristics of Glass to top cover solar panel surface. And to study the Load Carry capability of the solar panel top cover
- Exploration of the (piezoelectric) as a Secondary (auxiliary) Energy Harvesting System to combine with solar roadway.
- To calculate the amount of harvesting energy within the UK roadways.
- To Compare the Cost of 1 Kilometre Asphalt Roadway with Solar roadway.

5 Methodology

The Methodology of this thesis centre primarily on quantifying the challenges involved in the implementation of Solar Roadways, analysing the typical extreme conditions the solar panels and the associated structures are subjected to. The computational tools COMSOL Multiphysics and the PSpice software have been effectively utilised for the numerical predictions. This Methodology can be summarised as follows:

- A detailed work on the feasibility of putting through the Solar Roadway system the United Kingdom by covering total available road surfaces in the UK with solar panels demonstrated that the electricity generated from these solar panels are sufficient to provide power to the entire country for a twelvemonth.

- A methodology to analyse the effects of fast moving shadows on the yield of the solar panels has been developed using PSPICE and their results are validated via experiments.

- Using COMSOL Multiphysics software, the load bearing capacity of the existing materials to be used as panel cover is analysed and this methodology is envisaged to help future studies on the characteristics of future materials to be acquired for the Solar Roadways application.

- An energy harvesting method utilising piezoelectric elements proposes to harness the strain caused by the vehicles moving over the solar panel and this system can be used to overcome various losses in the solar panels for solar roadways application. A process for optimising locations of piezoelectric components, for the proposed energy harvesting system, and has been formalised using COMSOL Multiphysics software methods for future analysis.

- To analysis the characteristic of the solar roadway top cover material, the Granta Design Edupack Software has been utilised, the **(Acrylic**) Material has been elected for the purpose, the Buble Chart has been produced with limitation of transparent.

1.3 Review of existing knowledge

Astucia SolarLite began installing solar panel fit road studs as early as 1999 in the United Kingdom and has since installed them in over 10 localisations.

Figure 1: Astucia SolarLite Intelligent road studs have safely guided vehicles to the English port of Dover
(World Highways, 2010)

This can be considered the first iteration of the universal concept of solar roadways. Basically, the road studs functioned as smart RPM's or reflective pavement markers. They were initially utilised in areas of high speed traffic and poor weather conditions such as rainfall and haze. The road studs have already been shown to cut fatal accidents by as much as 70%. On February 2012, 105 Astucia Hardwired Intelligent Road Studs were installed on the roadside of the A41 carriageway just north of Telford, Shropshire and 200 Astucia SolarLite Flush Road Studs were installed in the core of the road giving drivers clearer guidance and visibility of the road ahead for a distance of 900m. Two Vehicle Activated Signs (VAS) were set up on either side of the route just before the connecting roads joined the main A41 carriageway with each VAS being controlled by radar. The studs were programmed to constantly emit low level light during the hours of darkness and if a vehicle were to surpass the speed limit on passing either of the VAS signs they would flash "Slow Down" with the hardwired studs automatically changing to full brightness, increasing the driver's visibility of the road out front (Clearview Traffic Group Ltd, 2008).

Solar Roadways Incorporated (SRI), founded by Scott Brusaw, is at the cutting edge of designing the first prototypes and is presently in the process of producing the first real application for the state of Idaho. In 2009 the United States Department of Transportation by way of the Small Business Innovation Research/ Small Business Technology Transfer Research (SBIR/STTR) put out a solicitation for some sort of paving material that could compensate for itself over its life. SRI applied and was awarded the Phase I research grant (SBIR&STTR, 2008). They built a 12- foot by 12-foot prototype solar road panel with LED displays with traffic lines and fully automated digital functioning. And this is the end of the beginning. Responsibility lies upon the engineering community to take this concept and see it through with applications in every aspect of transportation.

Brusaw imagines a future when the solar energy collected off the road would allow all-electric vehicles to recharge essentially anywhere, creating these vehicles much more economically feasible. The company has already been successful in completing the first phase of their Small Business Innovative Research contract. This contract was established upon the precondition that they get a fully-functioning prototype of their solar roadway concept in a car park. Car parks are good test sites for the solar panels because the vehicle traffic is lightweight and slow-moving, and the car park can be easily monitored 24 hours in 7 days per a week.

Brusaw also envisions the solar panels in driveways, playgrounds and residential streets. Since their success in building this car park prototype, Solar Roadways has been awarded a follow-up $750,000 for phase two of their contract Furthermore, Solar Roadways Inc. hopes to have a working prototype installed in the car park of a McDonald's in the near future (Scott Brusaw, 2013).

1.3.1 Solar Roadway Design Concept

There are various features that can be applied to solar roadways that would otherwise be Impossible, or increasingly heavy. First and foremost, the photovoltaic panelling is the backbone of the new concept. Inside the panel will be several functions and instruments. The LED lighting system is a multi-purpose tool that would be used for traffic lines, and real-time caution signs. The glass must be of a high impact strength that can withstand high acceleration and deceleration, all weather conditions, heavy point loads, sharp objects, shatterproof, fireproof, high traction, transparent enough to permit the light through but not to allow the glare back into the driver's eye. With regard to winter weather, the pane should have heating elements similar to that of a rear window of an automobile. This would eliminate ice build-up, simplify heavy snow removal, and remove heavy salt deposits in the urine System. All of these choices will be hermetically sealed in an airtight panel. Underneath the panelling can be recycled material that would otherwise be in a landfill. A standard road construction would require cutting and fill of soil. Depending on the place, fill may need to be hauled to the site at significant cost to the project. Graded aggregate base, or GAB, is used for stability, but perhaps non-volatile inorganic waste such as plastics could be used as fill for the roads. This would be another added environmental feature of the entire proposed system. A way of utilising an otherwise useless waste has been always a net positive, especially when it affects the environment. In cases of failure or lightning hit, each panel should have a stroke in order for the electrical pulse to be taken. This would ensure normal working conditions for the remainder of the road. With that reliability, the panels can be used to directly power the street lights, if need be. This would be the first example where the cost to municipalities would be immediately eliminated, full stop. Roadways are of varying width when taking into account the type of road, the number of lanes, and the width of lanes and shoulders. The panelling could be manufactured in varying dimensions, but perhaps a good standard for mass production would be 10-foot by 10-foot. This would get them both easily transportable and large enough so as to not have to waste time placing many smaller panels for the power of one great one. This would also fit perfectly for the standard 30-foot roadway using three panels. The panels would be linked by way of a bonding agent which is possibly one of the few instances that a petroleum by-product is needed outside of the manufacturing and shipping operations.

The solar road panels are divided into three basic layers:-

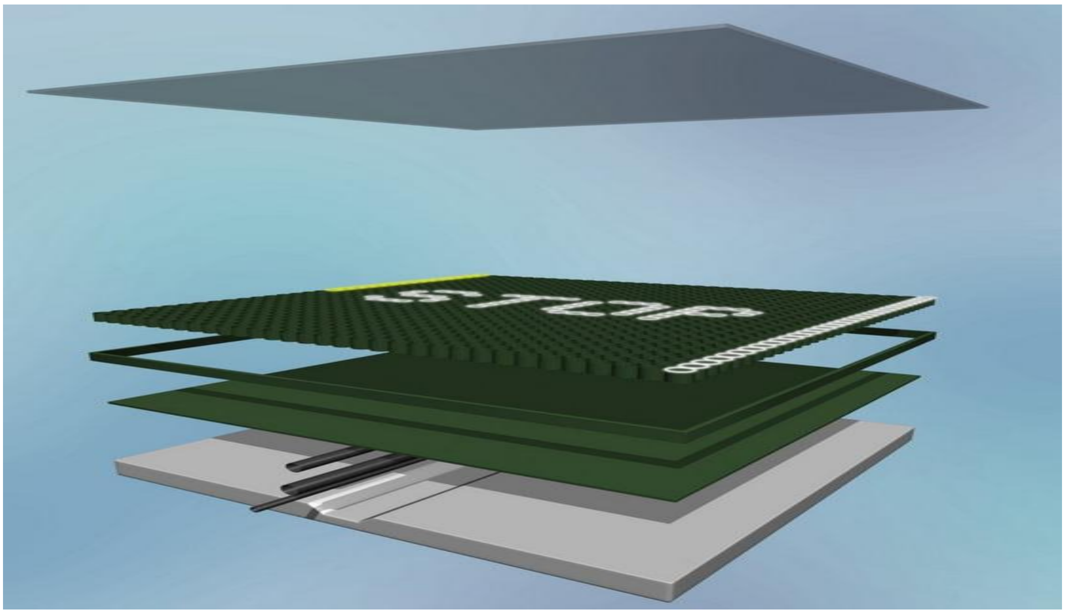

Figure 2: Simulation of three basic layers for solar roadway
(Scott Brusaw, 2013)

1.3.2 Road Surface Layer

As this is the top most layers of the assemblage, the material of Arclic has been selected for production, as imbedded with solar cell, from this layer the solar photon will hit the photovoltaic cells; surface layer should be transparent and high-strength. Also, this is done in such a material that it is rough enough to provide great traction to avoid the skidding of vehicles, the sunlight passes through it to the solar collector photovoltaic cells embedded within it, along with fitting LEDs and a heating element. And it is tough enough for handling today's heaviest loads under the worst conditions and it is made water-proof so that it can prevent electronics layer beneath it (Scott Brusaw, 2013).

1.3.3 Electronics Layer

Electronics Layer Contains a microprocessor board with support circuitry for sensing loads on the surface, controlling and monitoring the fixed heating element within surface layer. The material of aluminium has been selected for production this layer, as its contain all wiring and a microprocessor board, By implementing this technology no more snow/ice removal and no more school/business closings due to inclement weather in the snow falling countries. The on-board microprocessor controls, lighting, communications, monitoring, etc., which is fitted at every 12 feet distance; which can prove the Solar Roadways as an "Intelligent Highway System" (Scott Brusaw, 2013).

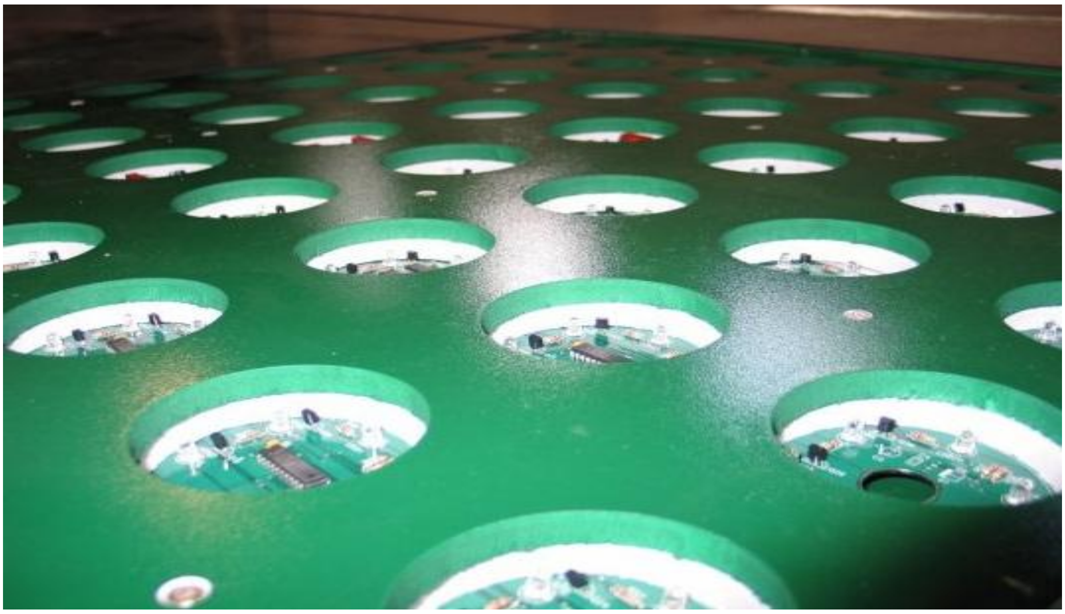

Figure 3: Prototype of Electronic layer for solar roadway
(Scott Brusaw, 2013)

1.3.4 Base Plate Layer

Through surface layer the sun photon reaches the electronics layer, therefore energy is gathered from the sunlight by the solar cell collector, then the harvested energy would be channelised to the power station via the base plate layer, the material of steel has been selected for production the base layer, as its supporting all other two layers above. The base layer also distributes DC power and data signals alike (phone, TV, internet, etc.) down-line to all homes and businesses connected to the Solar Roadway. The base layer is made weather proof, so that it can carry the electronic layer and the surface layer above it (Scott Brusaw, 2013).

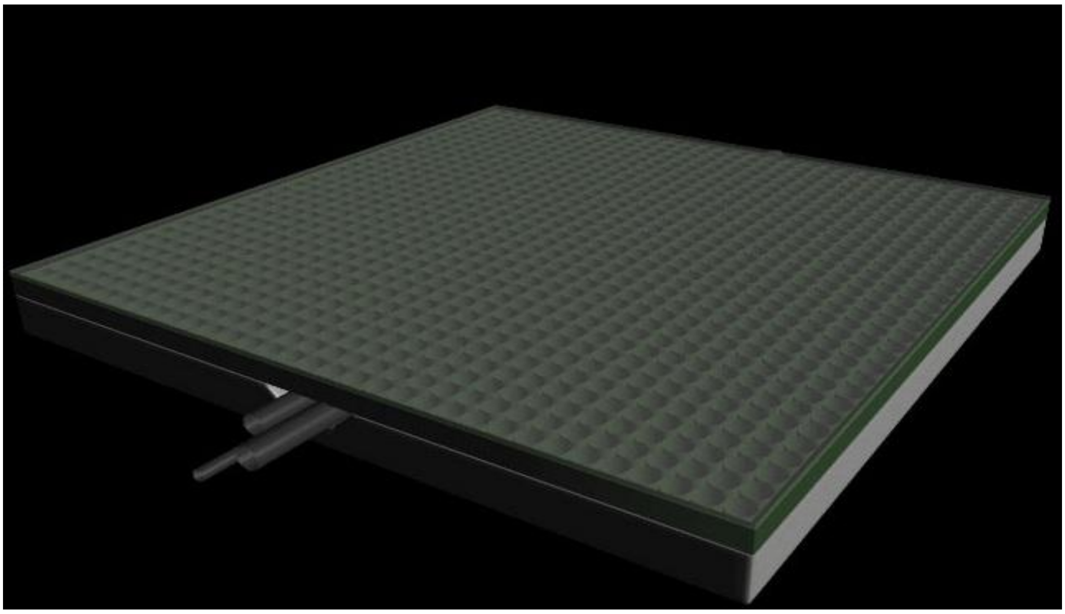

Figure 4: simulation of complete Assembled solar road Tile
(Scott Brusaw, 2013)

Chapter 2

Feasibility Study for the United Kingdom Roadways

2.1 Introduction

In this chapter, an analysis for predicting the feasibility of implementing Solar Roadways in UK is carried out. This analysis primarily provides quantification of the amount of electricity that can be generated if the total available road surfaces are covered with solar panels, while comparing the total possible energy output with the current electricity demand for the UK. Further, the predictions assume the use of the most efficient solar panel that is available in the market while considering mean daily global insolation data for the UK Region.

2.2 Lengths of the roads within the UK

Total length of roads available in the UK is calculated using the data taken from the Applied Research Associates report submitted to the Department for Transport in the UK (Department For Transport, 2013). In order to find the total length of available roads, Pedestrian, Driveways, collector roads and local roads under the local authorities' jurisdiction levels are taken into consideration. It is worth mentioning that in addition to these available roads, open spaces such as a car park, Roofs, footpaths, cycle paths and bridges which are readily available in the arena where people live can be covered with solar panels, so that the losses due to the long distance transmission of the electricity can be reduced. As there are not enough data available in these open spaces, only the roads are taken into consideration for the present predictions.

Table 1: The UK Roads Lengths by Road Type.

Road Type	Length (Thousand Mile)
Motorways	**2.2**
Trunk 'A' roads	**5.29**
Principal 'A' roads	**23.43**
Minor Roads	**214.08**
Total	**245.0**

The average widths of roads in the UK based on the (Department For Transport, 2013) are considered as 3.67 m (12 feet). Based on the above data, the total area in the form of roads available for conversion into Solar Roadways is estimated to be 558.7 mi^2 Or 1447 Million m^2 .

Total roads length and Area available in the UK is shown in Table 2.

Table 2: The UK Roads Lengths by Region.

Region	Percentage	Length (Thousand Mile)
England	**76 per cent**	**187.18**
Scotland	**15.0 per cent**	**36.75**
Wales	**9.0 per cent**	**21.07**
Northern Ireland	**N/A**	**N/A**
Total		**245.0**

- It may be noted that in the data provided in Table 2-2, in 2010, 76 per cent of the 245.0 thousand miles of road in Great Britain in 2010 was in England. 15.0 per cent were in Scotland and 9.0 per cent was in Wales.

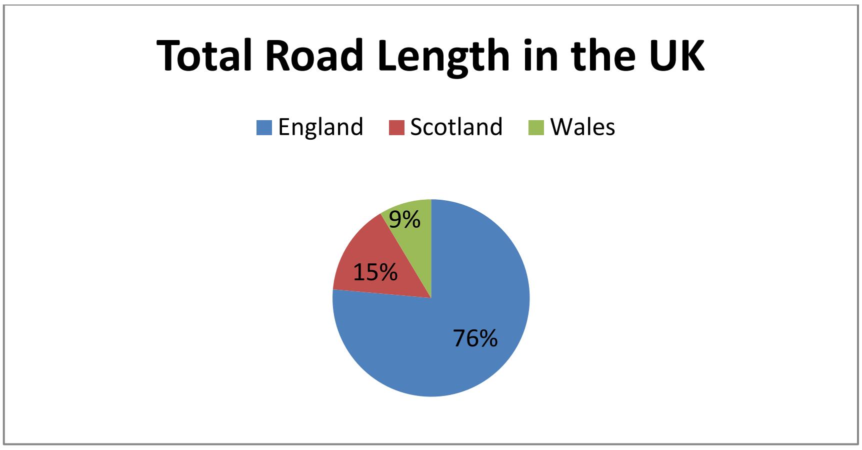

Figure 5: Total area available as roads in each Region to be covered by solar panels

Within England, the regions with the largest amount of road length were South West, which had 31.0 thousand miles, and South East, with 29.5 thousand miles. (UK Department for transport, 2013)

Figure 6: Motorway and trunk road network in Great Britain.
(Department For Transport, 2013)

2.3 Selection of solar panel

Solar panels for the calculation purpose are selected based on their efficiency to convert the sunlight falling on them into electricity. According to The EvoEnergy news report, the most efficient solar panel available in the UK market at present are the solar panel manufactured Sunpower Unconquered Sun solar technologies which has an efficiency of 16.0% (evoenergy, 2012). Thus Sunpower E20 poly solar panel is selected for the present calculations. The specifications for the Sunpower E20 poly solar panel at standard test conditions (Sunpower, 2013) is given in Table 3.

The specification for the solar panel is based on the standard test conditions (STC) of solar irradiance 1000 w/m2, air mass 1.5 and the cell operating temperature of 25° Celsius (Sunpower, 2013). According to the Sunpower manufacturing for solar cell, the efficiency of the latest solar cell has been exceeded 42%. Table 2-3 is show the data on the solar panel that it has been selected for the calculation. (Sunpower, 2013)

Table 3 Specification of the Sunpower E20 solar panel

Maximum Power	**250W**
Open circuit voltage	64.9 V
Short circuit current	6.46 A
Module Efficiency	42 %
Cell configurations	60 in series
Tolerance of Maximum Power	+5/-0%
Maximum Power voltage	30.1V
Type of cells	Polycrystalline silicon
Maximum Power current	8.30A
Dimensions (Length x Breadth x Height)	1644mm x 972mm x 50mm

2.4 Average daily local insolation also known as (solar irradiation)

Insolation (also known as solar irradiation) is a measure of the solar radiation received by given area over a given period of time The unit used for insulation is either/m2 or kWh/m2. The mean daily global insolation will give a measure of total solar energy available in each Region in the UK, In order to calculate the amount of electricity that can be produced by the solar panels, the solar insolation data for each county are required, so that the calculated amounts of electricity that can be produced by the solar panels are closer to the actual electricity that will be produced under real environmental conditions. The photovoltaic maps published by Natural Resources (N.C.Coops, 2000)

For the role of evaluating the mean daily global insolation, the following elements have been brought into thoughtfulness:

- Solar panel orientation is treated as horizontal for this case, as they are going to be laid along roads.
- Maximum and minimum available mean daily global insolation value take into consideration, so that an upper and lower limit estimate of the quantity of electricity that may be created by the Solar Roadway system can be looked (N.C.Coops, 2000).

Table 4 Mean Daily Insolation Data for each Regional in the UK.

Regional	Mean Daily Insolation (kWh/m2)			
	Latitude	Longitude	Minimum	Maximum
England	51' 50" N	3" 10" W	0.67	4.74
Wales	51' 55" N	3" 18" W	0.55	4.33
Scotland	55' 82" N	4' 2" W	0.44	4.13

- The period for which the mean daily global insolation is considered is annual. This consideration is made as would be require data for calculation purposes only. The period can also be considered on a monthly or daily basis instead of annually, for more accurate calculations (SECO, 2014).

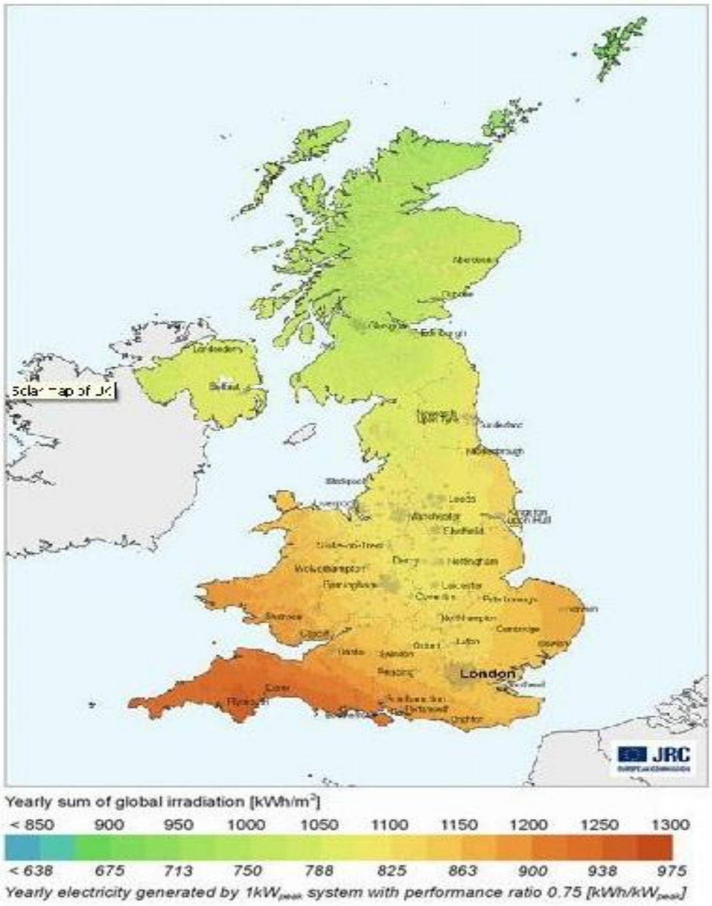

Figure 7: UK Mean Yearly global insolation

(REUK , 2012)

Table 5: the UK Average Insolation in kWh/m2/ Yearly

Regional	Yearly sun of Global Irradiation (kWh/m^2)	Yearly Electricity Generated by 1KW
England	1200	900
Wales	1150	863
Scotland	950	713

2.5 Energy producers across the country

Based on the available length and width of the road for each region, total area available for converting into Solar Roadways is calculated. Theme based on the average daily sun peak hours (i.e. Number of hours in a day a location will have solar irradiation of 1000 watts per square meter), total sun peak hours available for a year in each region is calculated. Finally, based on the calculated area, total yearly sun peak hours in each Area and using the data from the selected solar panel, the energy that can be produced in each region by solar roadways is calculated and shown in Table 5.

So a total of 8424 x 105 TW-hour of energy per year can be produced in England, Wales and Scotland, by hiding all the roads available with the solar panels based on the maximum yearly insolation value is 884.5 TW-hour of energy per year. Realised that the electricity use in the UK is 325.9 TW-hour of energy per year (Department of energy and climate change, 2011) it may be estimated that Solar Roadways if implemented in the UK to supply power to a utmost of 66 cities across the Kingdom.

Table 6: Total energy produced from Solar Roadways in the UK.

Regional	Total Road Length *Mile* (Thousand)	Total Road Length *m* (million)	Total Road Area m^2 (Million)	Total Yearly insolation (kWhr/m2)	Total Energy produced (KWh) (Million)
England	187.18	3000.9	6.84	1200	8208
Scotland	36.75	57.9	0.13	1150	149.5
Wales	21.07	33.7	0.07	950	66.5
Total	**245.0**	**3092.5**	**7.05**		**8424**

Table 6 shows the total area available as roads in each Regional and the energy produced by covering all these roads with solar panels. This table shows that England, Wales and Scotland can benefit maximum from the solar roadway system.

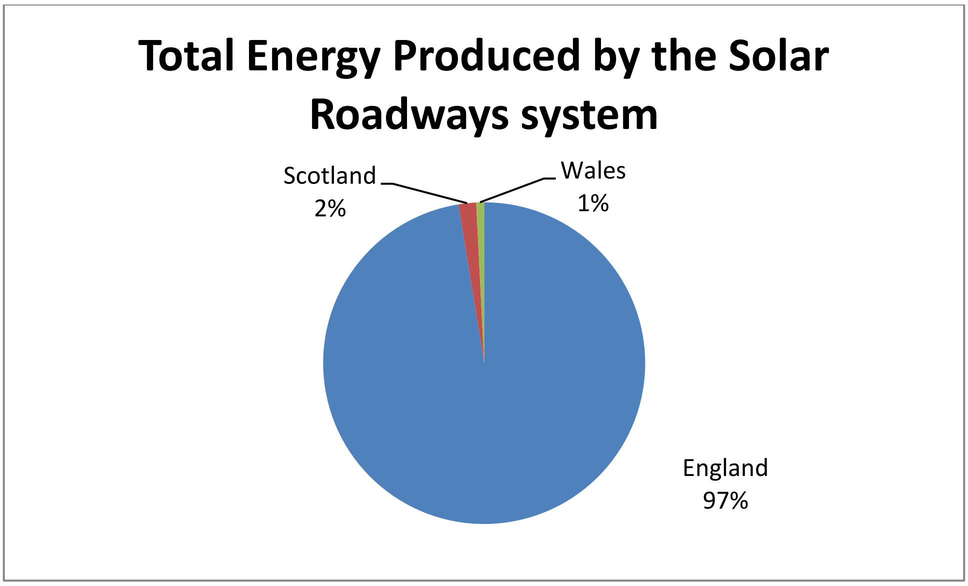

Figure 8: Energy produced in each province by the Solar Roadway system

2.6 Summary

In this chapter, a feasibility study for a Solar Roadway system in the UK has been conducted by calculating the total area available in the forms of roads and total amount of electricity that can be generated by covering these open spaces with solar panels. Based on the average values of available insolation, the energy produced in each region has been calculated. It is clear that the electricity generated just by covering all the roads in the UK with the solar panels, would be sufficient to exceed the power demands of 66 cities similar in size to Birmingham which can benefit maximum from the solar roadway system.

Chapter 3

Power output variations due to influence of fast Moving Shadow over the solar panel

3.1 Introduction

The effect of shades on solar panels has been studied through software simulations in the recent past in an effort to maximise solar panel output. However, the shade effects on solar panel considered have been limited to the obstructions caused by buildings or trees to the sunlight falling over the solar panels. These types of shades always depend on the position of the sun. The effect caused by these shades remains for a very long duration and hence considered to be quasi-static in nature. The effects caused by the shadow on the electricity yield of solar panels will be present for hours to days. Shading over 5% of the area of the solar panel can decrease output power to as low as 50% (A. Ubisse and A. Sebitosi, 2009). Nonetheless, in Solar Roadways application, in addition to the cases studied above, vehicles moving over the solar panels cause fast moving shadows to appear over the panels. Typically it is expected that the outcome of these shades on the electricity yield of solar panels will be present for only a few minutes depending on the velocity of the vehicle moving over it. Hence, in solar roadways application, it is necessary to consider the effect of this pattern of shades. In the present study, PSpice software has been used to imitate the effects of fast moving shadows on the solar panels and these consequences are justified by simulating software.

3.2 PSPICE software

The name PSpice is an acronym for Personal computer Simulation Program with Integrated Circuit Emphasis. The Spice was originally an open source electronic analog circuit simulator, developed at the University of California (Richard P. Andresen 5Spice, 2014). Spice has been developed from Spice and it can be utilised for both analogue and digital circuit simulation. In the present work, a popular version of this software Cadence PSpice

A/D has been used. With this software, programs which symbolise the equivalent electrical circuit. The solar panel is synthesised and their yields have been read for various typical Inputs. Therefore, these plans can be applied to simulate the response of solar panel production, Without the need of making the complete real electrical circuits. In this analysis, equivalent electrical circuit of the solar panels is modelled using the simple current source, voltage source, diodes and resistors that are used in the PSpice library and the effect of sun on the production of the solar panels have been measured.

3.3 Equivalent electrical circuit of the solar panels

The equivalent electrical circuit for the solar panels (Richard P. Andresen 5Spice, 2014) The solar radiance received by the solar cells is employed as an input current to a voltage controlled current source. This is founded on the equation 3-1.

$$I_L = \frac{iscm}{1000}\ G \text{..................................Equation 3-1}$$

(Christiana Honsberg & Stuart Bowden, 2013)

Where I_L Represents the photocurrent, G denotes the solar irradiance in W/m^2 And the short circuit current of the solar module measured under a standard test condition (Gorman, 2013). The standard test conditions for the solar panels are solar irradiance value of 1000 W/m^2And the solar cell temperature of 25°C and an air mass coefficient of 1.5.

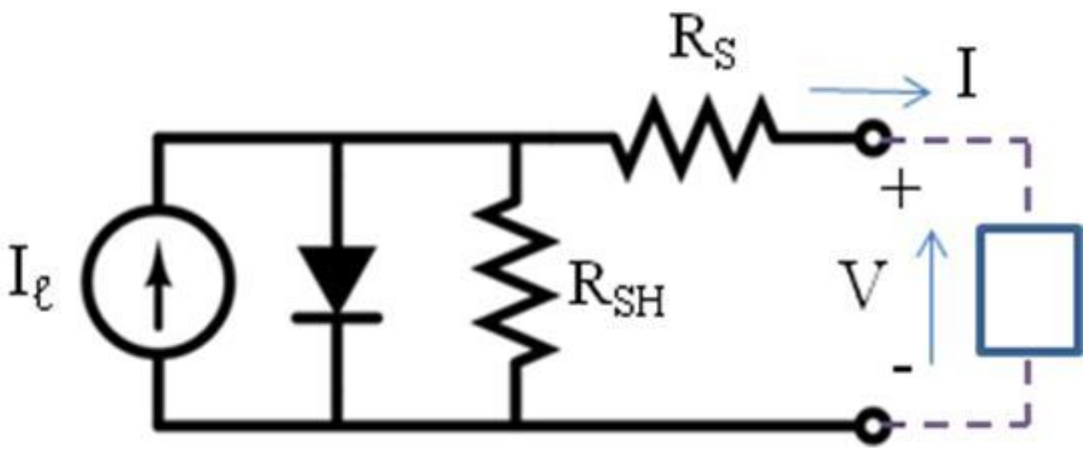

Figure 9: Equivalent electrical circuit model for solar panels
(Christiana Honsberg & Stuart Bowden, 2013)

In the equivalent electrical circuit model for the solar panels shown in Figure 6, a series resistor R_S, shunt resistor R_{Sh} And diode D is also included. The series resistor included in the example represents the series resistive losses which are present in the actual solar panels. These losses are made primarily due to the drift of current generated by the solar cells through the emitter and the basis of the solar cells and partly due to the contact resistances (Christiana Honsberg & Stuart Bowden, 2013). A series resistive loss reduces the fill factor (Fill factor is the ratio of actual maximum obtainable power to the product of open circuit voltage and short circuit Current) and the short circuit current of the solar cells. In order to include shunt resistive Losses which are present in the actual solar panels, a shunt resistor has been included in The model. It may be noted that shunt resistance is too mentioned to as parallel resistance. Shunt resistive losses are caused in the solar cells primarily due to manufacturing defects present in the solar cells. Shunt resistive losses are also known to be larger when the sunlight falling over the solar cells are at low levels. In practice, it has been made that it is difficult to get an ideal (Current & Voltage) characteristic in this class of devices. In decree to overcome this, a diode is included in the equivalent electrical circuit model. So, the (Current & Voltage) characteristics of the equivalent electrical circuit of the solar panel are based on the equation

$$I = I_L - I_0 \left(\frac{V+IR_S}{e^{nV}T-1}\right) - \frac{V+IR_S}{R_{Sh}}$$ ....Equation 3-2

(Christiana Honsberg & Stuart Bowden, 2013)

where *I* is the output current from the solar cell, is the dark saturation current (i.e. Diode leakage current density in the absence of sunlight (Christiana Honsberg & Stuart Bowden, 2013)), *V* is the voltage across the output terminal, and are the series and shunt resistance respectively, *n* is the diode ideality factor which is a number between 1 and 2 and *VT* is the thermal voltage depending upon the absolute temperature *T* iKelvinin. Short circuit current for the equivalent electrical circuit model of the solar panel is given by substituting *V* = 0 (i.e. The output voltage is being set to zero) in the IV characteristic equation 3-2:

$$I_{sc} = I_L - I_0 \left(\frac{I_{sc}R_S}{e^{nV}T-1}\right) - \frac{I_{sc}R_S}{R_{Sh}}$$ .... Equation 3-3

(Christiana Honsberg & Stuart Bowden, 2013)

Where I_{sc} Is the short circuit current of the solar panel.

Open circuit voltage for the equivalent electrical circuit of the solar panel is obtained by substituting *I* = 0 (i.e. The output voltage is set to zero) in the IV characteristic equation 3-2. It is known that the open circuit voltage is independent of the series resistance value and also the shunt resistance value (Luis Castaner and Santiago Silvestre, 2002). Hence those terms involving the series and shunt resistance value in the IV characteristic equation 3-2 can be neglected, to obtain the Expression for the open circuit voltageV_{oc}:

$$V_{oc} = nV_T ln\left(1 + \frac{I_L}{I_o}\right)$$ ....Equation 3-4

(Christiana Honsberg & Stuart Bowden, 2013)

In a typical solar panel, several solar cells are connected in series and parallel. In order to model a solar panel into an equivalent electrical circuit, some premises have to be taken in. The shunt resistances of the solar cells are assumed to be larger, so that its effects can be neglected, and the photo generated current I_L Is assumed to be equal to that of the short circuit current *Isc* on the solar cell (Luis Castaner and Santiago Silvestre, 2002). The scaling rule for a solar panel where the number of cells in series is *NS* and the number of cells in parallel is *no* results in:

$$I_M = N_P I \quad , \; I_{SCM} = N_P I_{SC} \quad ,3\text{-}5a$$

$$V_M = N_S V \quad , \; V_{OCM} = N_S V_{OC} \quad ,3\text{-}5b$$

$$R_{SM} = \frac{N_S}{N_P} R_S \qquad , 3\text{-}5c$$

(Christiana Honsberg & Stuart Bowden, 2013)

Where the subscript *M* stands for the solar panel module and while variable without the Subscript *M* represents the parameter associated with a single solar cell.

3.4 selections of solar panel for speech software

Parameters associated with the Sunpower E20 solar panel are obtained from the manufacturer Specifications and are employed for synthesising the PSpice equivalent electrical circuit model. The Sunpower E20 solar panel is considered as one of the most efficient and cost effective solar panels available at present market. For PSpice simulation the Sunpower E20 solar panel was used. These panels are made of crystalline silicon solar cells. These cells are permanently encapsulated between a tempered glass cover plate and a back seat which is secured in an aluminium frame (evoenergy, 2012). Specifications of the Sunpower E20 solar panel under standard test conditions are given in Table 7.

Table 7: Specifications of Sunpower E20 solar panel

Maximum Power (P_{max})	**250W**
Open circuit voltage (V_{oc})	64.9 V
Short circuit current (I_{sc})	6.46 A
Tolerance of Maximum Power	+5/-0%
Maximum Power voltage	30.1V
Maximum Power current	8.30A
Dimensions (Length x Breadth x Height)	1644mm x 972mm x 50mm

3.5 Verification of solar panels power and specification via {spice} software analysis.

In the equivalent circuit modelled for the solar panel in PSpice, shunt resistance is neglected and diode ideality factor is taken to be unity. The issues from the simulation in PSpice has been utilised to verify the tested specification of the selected solar panel given in Table 7. The Voltage – Current (VI) characteristic curvatures and the power curve generated in PSpice are shown in equation 3-2 and 3-3 respectively. In voltage – current (VI) characteristic curve the open circuit potential is the voltage obtained when the current in the circle zero and the short circuit current is the current obtained when the electric potential in the circle is zero. The peak value of the power vs. voltage curve gives the maximum power. The open circuit potential, short circuit current and maximum power obtained from the figures is 30.1V, 8.30A and 250W respectively, and adapts to the solar panel specification given in Table 7. This shows that the holdings of the equivalent electrical circuit model for solar panel in PSpice and the actual solar panel to agree closely with an erroneous belief of almost 1 to 2%.

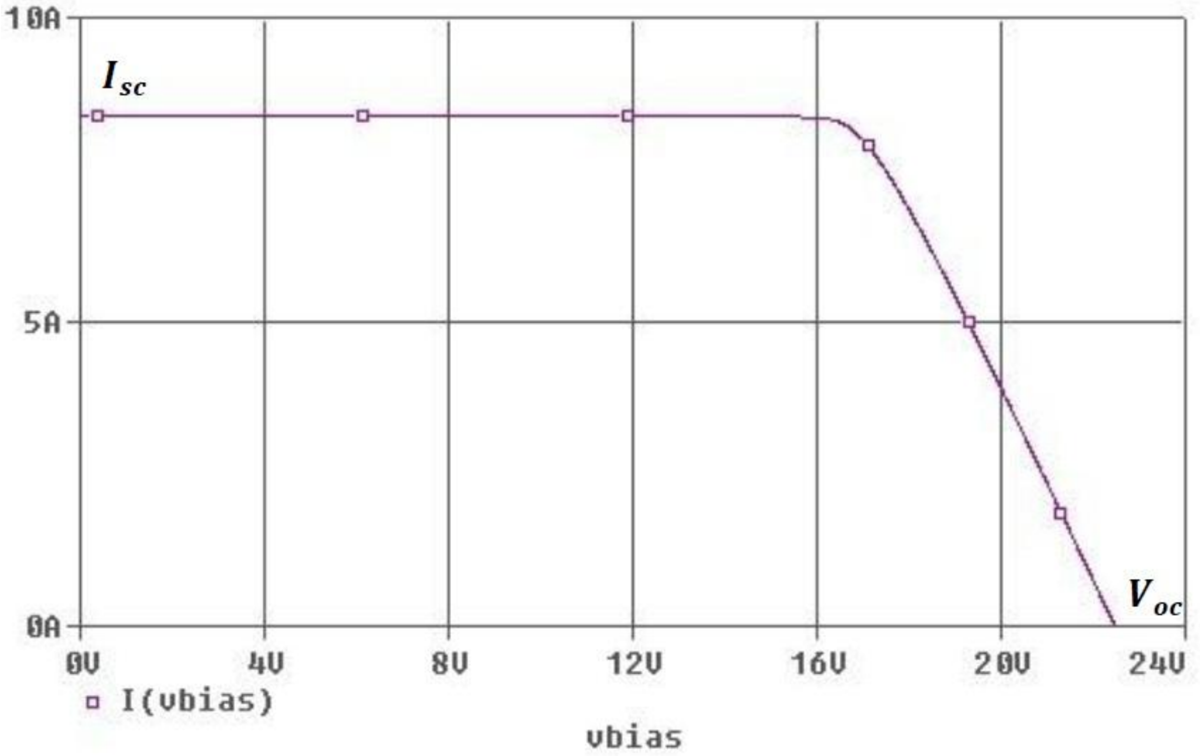

Figure 10: Voltage and Current characteristic curve for PSpice Software of the selected Sunpower Slolar Panel

3.6 Shadow effect analysis

In analysing the effects of shades made by the vehicles moving over the solar panels, the swiftness of the vehicle and the duration of the vehicle are the two most important elements to be considered for calculating the time for which the tincture will be present over the solar panels. In the present analysis, three cases of vehicles are considered, namely, a tractor semi-trailer, an intercity bus and a full size automobile. All three types of vehicles are considered to be travelling at a steady speed of 13.889 m/s (31 mi/hr). At the beginning of the simulation the solar irradiance is considered to be at 1 KW/m^2 Which is the standard test condition parameter. As the vehicle begins to travel over the solar panels, area of the solar panel covered with shade will increase and when the solar panel is fully hidden by the vehicle, solar irradiance received by the solar cells is believed to arrive at a value near to zero. The solar irradiance value remains at zero for a few seconds as the duration of the vehicle is larger than the duration of the solar panel considered for the psychoanalysis. It is expected that condition will cause a sudden fall in power output from the solar panel. When the vehicle begins to run off from the solar panel, area of the solar panel covered with shade is expected to decrease and the corresponding solar irradiance value received by the solar cells is expected to increase and to reach the value of 1KW/m^2 When the vehicle completely moves away from the solar panel, the power output from the solar panels is expected to increase and to reach its full output level.

3.6.1 Time calculation

Based on the speed and distance of the vehicle moving over the solar panel, time taken by The vehicle to traverse over the solar panel is estimated. In all of the time calculations, the Length of the solar panel is considered as 1500 millimetres. When speed at which the vehicle Movements over the solar panel is considered as 13.889 m/s (50 km/h), the time taken by the Vehicle to move over solar panel can be calculated and are tested in Table 8.

Table 8: Time taken by the vehicles to cross over solar panel

Vehicle category	Lorry semi-trailer	Coach	Full size normal Car
Speed	13.889 m/s	13.889 m/s	13.889 m/s
Vehicle length	23 m	14 m	4.9 m
Total time to cross Solar panel	1.77 Sec	1.126 Sec	0.471 Sec
Time duration for Complete solar panel Cover	1.534 Sec	0.890 Sec	0.235 Sec

3.6.2 Results from PSpice Software

In the present study on the shade effect caused by vehicles moving over the solar panels, analysis is performed between 0 to 10, and at the 6th second of the analysis the vehicle starts to pass over the solar panels. When the solar panels are fully covered by the shade, the amount of sunlight falling on the solar panels is taken as zero. To further study the effect on multiple panels, two solar panels, each with an output of 250W are connected in series. At any given instant only one panel is overlaid by the moving shade while the other panel receives full sun. It may be mentioned that in practice the shade may not comprehend the solar panels fully and the sunlight level may not exactly reach zero. Nevertheless, for analysis purpose these simplifications are made. As expected, the PSpice simulations show that the shade caused by a vehicle passing over the solar panel, will stimulate a sudden drop and advance in the power output from the solar panel as indicated in Figures 8-9-10. This sudden drop and rise in the power output, depends mainly on the speed and length of the vehicle. As the velocity of the vehicle increases the time duration between the fall and rise of the power output will begin to fall. Likewise, as the distance of the vehicle increases, the time duration between the fall and rise of the power output will begin to increase. It is worth pointing out for the solar roadways application, the system that is needed to link the power created by the solar panels to the grid, must be able to run with these rapid variations in the force due to fast moving shadows. The simulation study presented in this study provides an insight into the required power conditioner design.

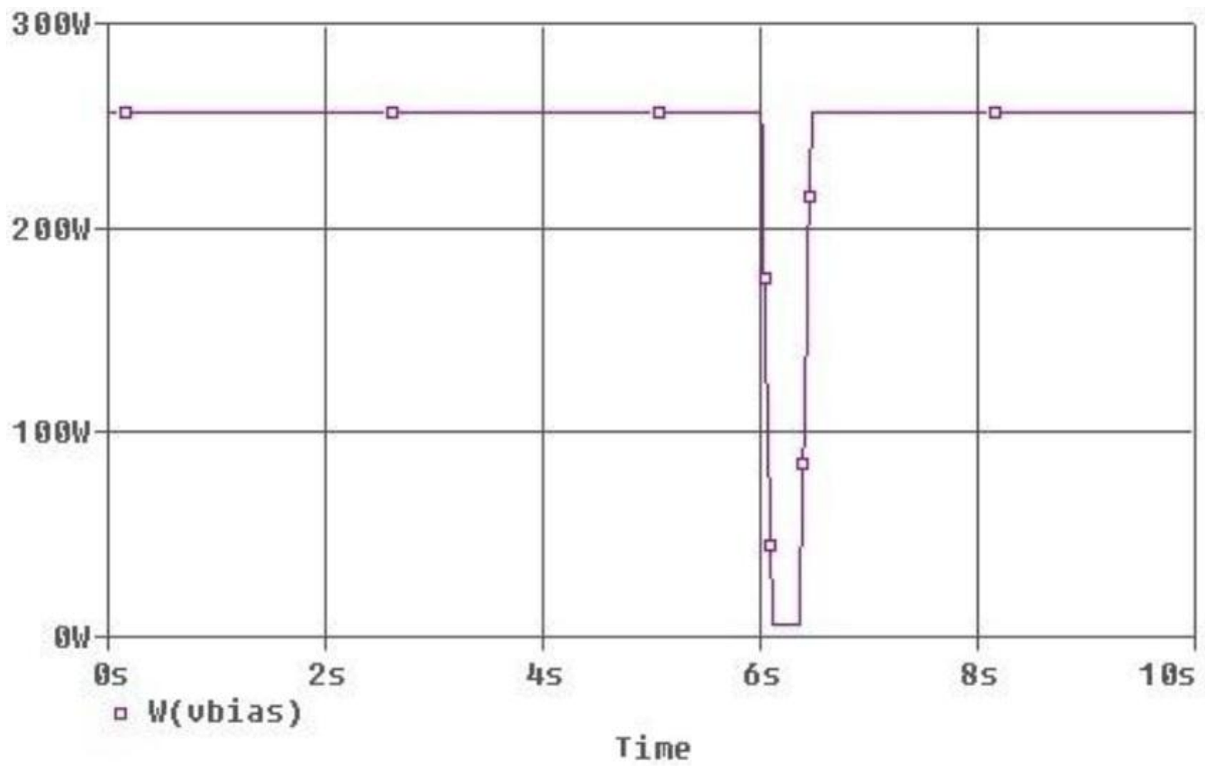

Figure 11: Power vs. Time curve (shading effect caused by a car moving over the solar panel with a velocity of 50 km/hr.)

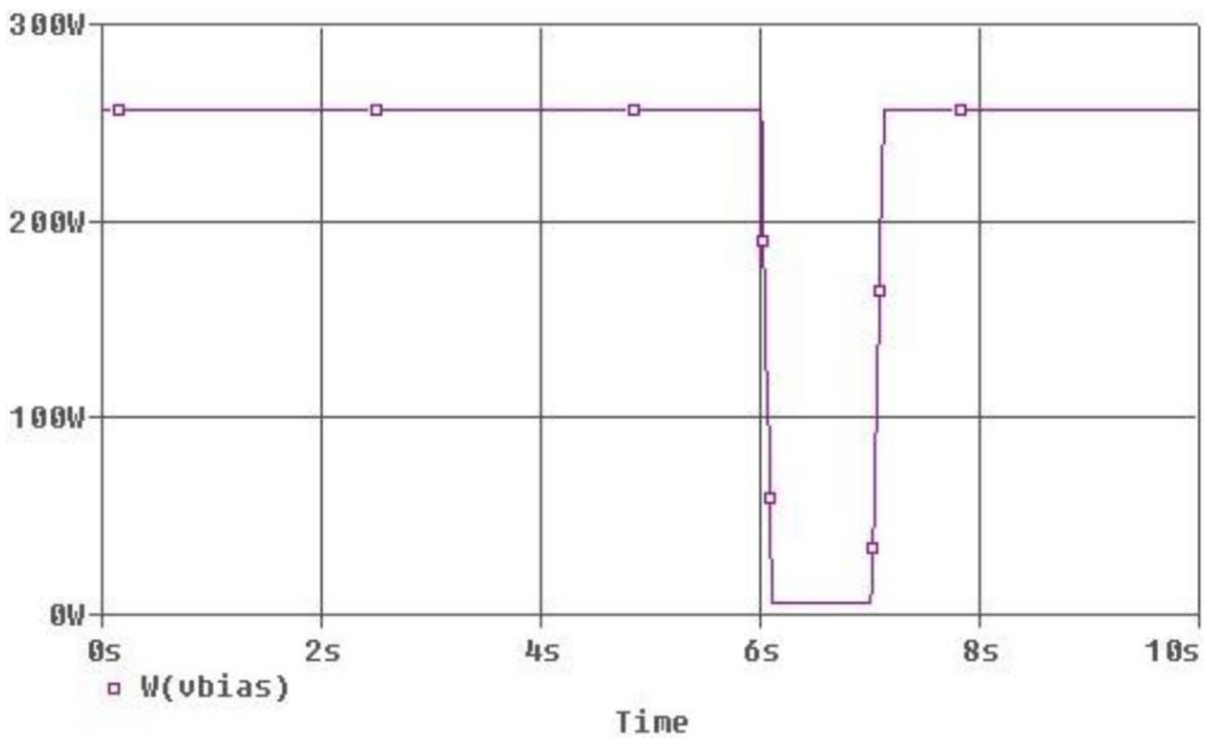

Figure 12: Power vs. Time curve (shading effect caused by a Coach moving over the solar panel with a velocity of 50 km/hr.)

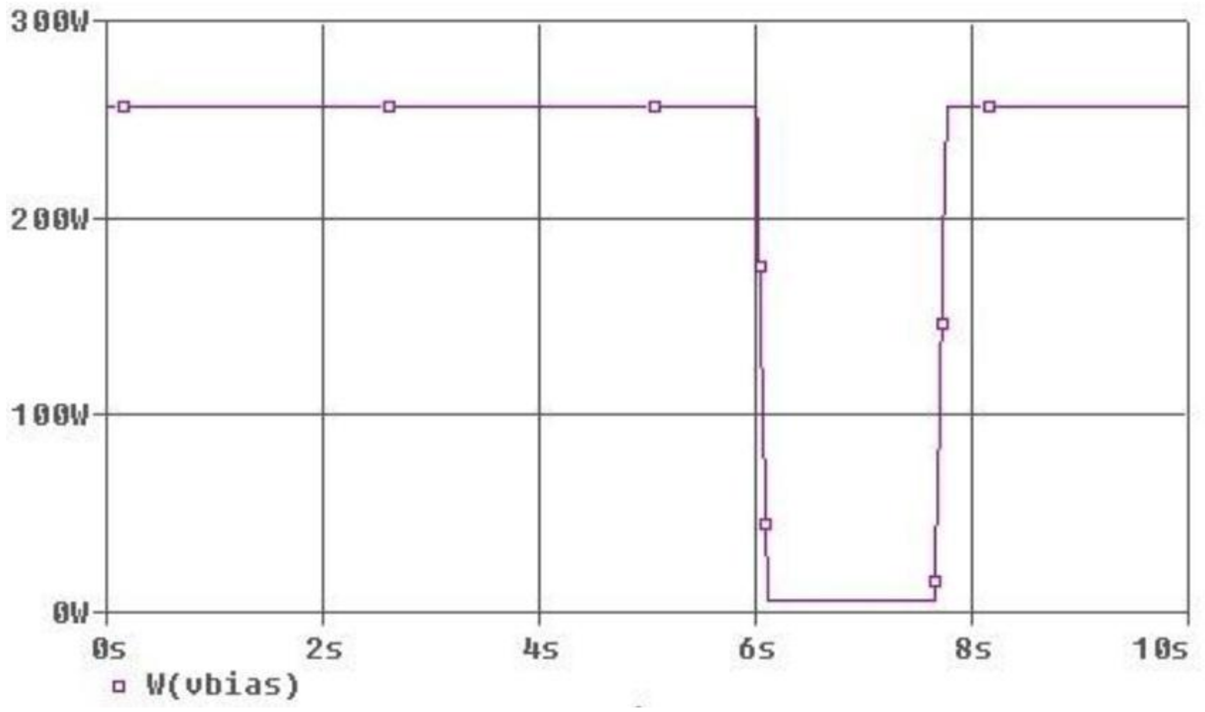

Figure 13: Power vs. Time curve (shading effect caused by a Lorry semi-trailer moving over the solar panel with a velocity of 50 km/hr.)

3.7 Summary

In this chapter, the effect of fast moving shade on the production of the solar panels, caused by the vehicle moving over it and various other losses that are affected by the Solar Roadways application has been considered. The quantity of energy deprivation in the solar panels has been found to be pendent on the durations and speeds of the vehicle. This analysis demonstrated how the solar panels behave when the solar irradiance value are higher or lower than the standard test condition value of 1000 W/m2.

Chapter 4

The characteristic of solar panel top cover Glass

4.1 Introduction

Solar panels for the current power generation applications are made to use up on loads due to hail, the weight of collecting snow and hard winds. Nevertheless, in the solar roadways application additional loads such as the burden due to vehicle moving over it and people walking over it are present. In other words panels have to withstand loads that are normally taken by the roads and walkways in addition to the typical environmental loads. Therefore, the solar panels to be used for this application, must deliver the necessary structural strength to get on the vehicle load moving over it while possessing surface properties similar to those of traditional roads, hence that the vehicles moving over it will have sufficient traction to drive and finish safely in slippery conditions like rain and snow. To satisfy these requirements, it is quite obvious that the traditional materials that are used for manufacturing the current solar panels are not suitable for solar roadway applications. Hence, there is a need for studying the load carrying capacity of the existing glass and other material characteristic that are available at present that can be used as a cover for the solar panels. Granta Design Edupack Software has been utilised to examine the character of selected Material in the solar roadways application. The Granta Design CES Edupack has many study types, such as Young Models, Density, Material Cost, material Strength and material capability (Jum. Mukasurat, 2011). Furthermore, the COMSOL Multiphysics has been used in the present study to ascertain the feasibility for different vehicular applications and for suggesting future material and geometrical properties.

4.2 Granta Design CES Edupack.

Granta Design CES Edupack is engineering simulation software, which has the capability to analyse material characteristic. Granta Design are the materials, information technology experts, providing the world's leading teaching resource for materials and process education, CES EduPack, and working with leading engineering enterprises to help them manage materials data and make materials-related decisions. Granta began as a spin-out from Cambridge University Engineering Department. CES EduPack supports and enhances teaching across a broad range of engineering disciplines and from first-year to post-graduate courses. EduPack is developed by the Granta team in collaboration with the worldwide community of EduPack users and with Granta founder, Professor Mike Ashby by the University of Cambridge (Jum. Mukasurat, 2011). CES EduPack has developed dramatically in recent years. Once best-known for specialist materials selection tools, its nature and applications have expanded as Granta Design and Professor Mike Ashby added new resources and software features in response to user feedback. Today, an increasing number of universities use EduPack across multiple courses, even as a campus-wide resource. EduPack is used from first-year to masters level and in support of a wide range of different teaching approaches. This Software is used to study the characteristic of selected Material in the solar roadways application. The Granta Design CES Edupack has many study types, such as Young Models, Density, Material Cost, material strength, and material capability.

4.3 Material selection

Based on an extensive literature review of road and landing mats it was determined that the best materials for use in the structural layers of the solar road panel are steel, aluminium, and Acrylic. Aluminium is one of the most popular materials for use in landing mats, proving that structures made from the material are able to withstand mission critical static and dynamic tire loads (R. Rollings, 1975). Referable to the relative material properties of aluminium and steel it is known that steel should do a more honest job of withstanding the loading from vehicle tires at a lower cost though also at a higher weight. Lastly, it was found that multiply Acrylic panels are able to withstand repetitive loading on poor sub-bases without failing (T. Rushing and J. Tingle, 2009) .

Referable to the necessities of the prototype design Acrylic was chosen as the ideal structural material. In increase to being low cost and light weight it is likewise the easiest to make a research paradigm for as either the aluminium or steel options would have necessitated a custom casting operation, which is a really expensive and difficult procedure. Further analysis using structural testing and finite element modelling will be executed to insure that this is the optimal material choice.

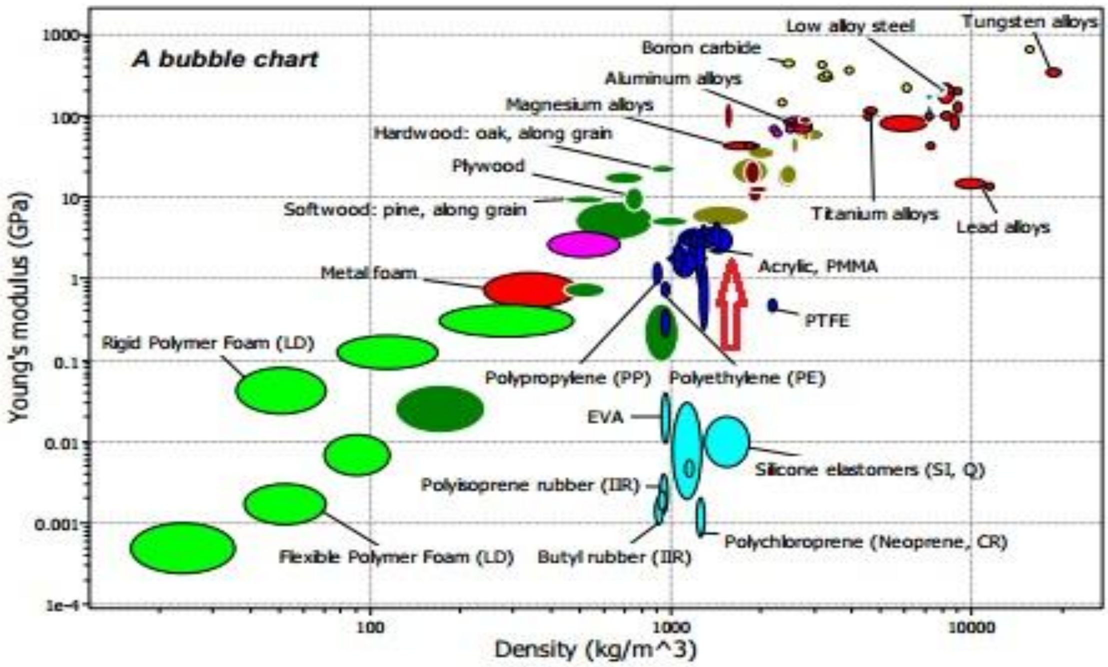

Figure 14: Acrylic bubble chart of young's modulus (e) against density (ρ) from Granta design Edupack.

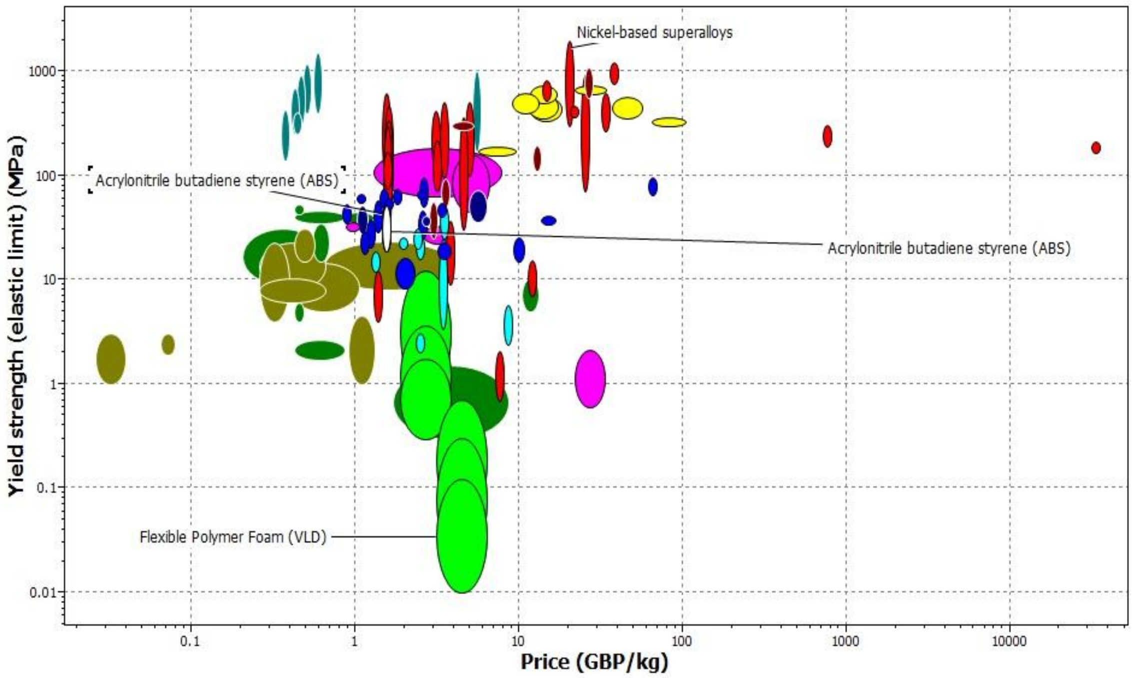

Figure 15: Acrylic bubble chart of young's modulus (e) against Price (GBP/Kg) from Granta design Edupack.

4.4 Analysis dynamic and Static characteristics via COMSOL software.

COMSOL Multiphysics is engineering simulation software, which has the capacity to analyse engineering problems that require many physics to be paired together. This software has easy steps for modelling the geometry, defining their material properties, meshing, specifying their physics, working out and visualizing results (COMSOL, Inc, 2014) In the present analysis, structural mechanics module of COMSOL Multiphysics has been used.ltiphysics has been employed. In particular, this module is applied to study deflection under typical loads encountered in the solar roadways application. The structural mechanics module has many study types, such as stationary, Eigen mode, parametric, quasi-static, transient, frequency response and pre40 stressed included in it. This module also has an interface for the piezoelectric devices which is employed in investigating the possible mechanical stress induced energy harvesting from the solar panels.

4.5 Panel Model for COMSOL Analysis

The basic solar panel consists of solar cells, which are permanently encapsulated between a tempered glass top plate and a back seat which is fixed in an aluminium frame (Sunpower, 2013). Likewise, the solar roadways panel must also have strong base layers which can accommodate the solar cells and their associated electrical systems to tap the force created by the solar cells and join it to the grid connection system. In order to cover this base layer, a top cover plate must be utilised. This home base must be lucid enough to tolerate the sun to run through it and also have high force to resist the load of vehicles going over it. In summation, this top cover plate must also be sufficiently rough in order to provide enough grip for the vehicles (Scott Brusaw, 2013).

Table 9: Acrylic Properties

Material Properties	Acrylic plastic
Young's Strength	**69 MPa**
Density	**1190 (kg/m^3)**
Cost	**1.2 GBP/kg**

The analysis purpose consists of a vertically hollow square base layer with sides 4 meters in distance, 0.5 metres in height and 0.1 meters in thickness. This base layer is considered to be made up of concrete, and covered with a transparent cover of size 4 meters and thickness 0.01 meters made up of Acrylic plastic. The Acrylic sheets have a forging temperature range of -40°C up to 93°C (Granta Edupack, 2014), and the elastic properties are simulated to remain invariant in this temperature range.

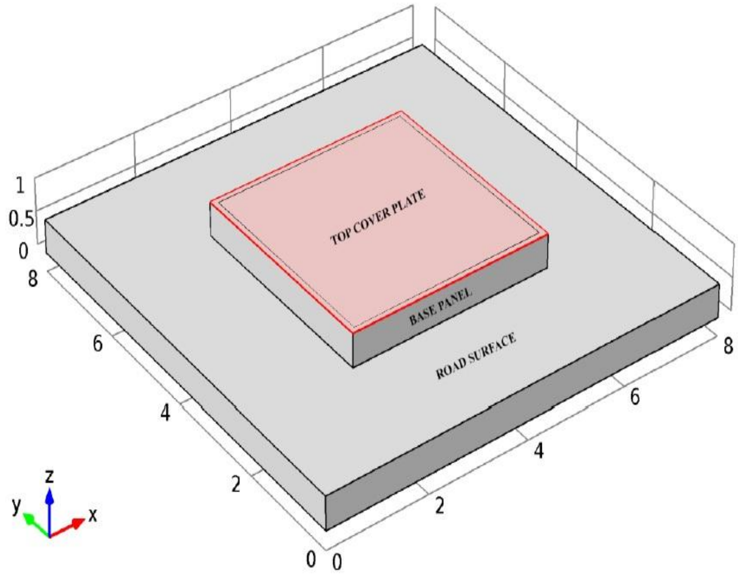

Figure 16: Solar Roadways panel model for COMOSL Multiphysics analysis

4.6 Selection of Standard Loads for solar roadways panel analysis

As the solar roadway panels are to be laid over the existing roads, the primary loads acting on the solar roadway panels are the vehicle loads. For the analysis, the loads associated with the vehicles are selected based on the specification from Department for Transport in the UK.Two types of loadings, H loading and HS loading are given by. H loading consists of a two axle Lorry and HS loading consists of a Lorry with semi-trailer (Department for Transport, 2003). In general, there are four standard classes of highway loading conditions, namely H15, H20, HS15and HS20. The number following the H and HS letter denotes the gross weight in tons of a standard Lorry. In the analysis of the solar roadways panel using COMSOL Multiphysics, H20 loading standard as displayed in Figure 14 is used. The gross weight of the Lorry is taken to be 18143.7 kg (40000 lbs.), while the front and the rear axle weights are respectively 3628.7 kg (8000 lbs.) and 14515 kg (32000 lbs.) (Department for Transport, 2003)

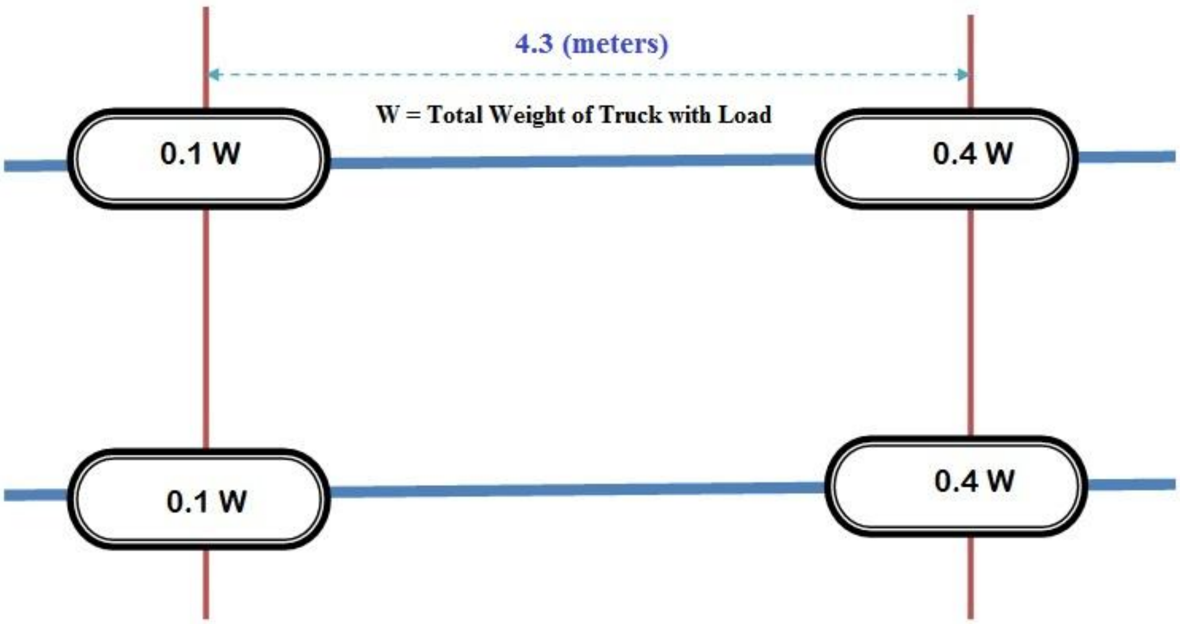

Figure 17: Standard H Lorry loading taken from Standard Specifications for Highway Bridges by Department for Transport
(Department for Transport, 2003)

4.7 COMSOL analysis procedure

The essential steps taken in the COMSOL Multiphysics analysis are presented in Figure 16. The foremost measure in the COMSOL Multiphysics analysis considers the global definitions such as parameters and variables that are employed in the analysis. The global parameters such as the weight of the truck and the initial posture of the truck front axle, i.e. the placement from which the warhead of the truck start to roleplay along the solar roadways panel are chosen. The second step defines a theoretical account of the solar roadways panel. As part of this step, local definition, such as a local coordinate system must also be redefined. Then, the geometry of the model is defined using the geometry node in the software. The model consists of a base layer and a top cover plate. The size of the base layer is (4m x 4m x 0.5m) and that of the top cover plate is (4m x 4m x 0.01m). Following the geometric definition of the model, the materials for the base layer and the top cover plate are defined. The base layer is assigned as concrete material and the top cover plate is assigned as acrylic plastic. Properties of these materials are given in Table 8. The third step in the analysis defines solid mechanics interface properties which resides under the structural mechanics module. These properties include fixed constraints and definition of the positions where load due to vehicle act on the solar roadways panel constraint i.e. the displacements are zero in all directions. The fourth step in the analysis defines meshes elements of the model. Free tetrahedral type of mesh elements is selected and the size of the elements for each boundary was defined separately. The fifth step in the analysis defines the type of study that has to be performed on the model. In this analysis parameter type of study is performed. The parameter selected for the study is the position of the front axle of a Lorry. For the analysis, geometric nonlinearity is also considered, due to possible large displacement to be caused by the Lorry load. In the final step visualisation of the various results and the corresponding analysis is performed.

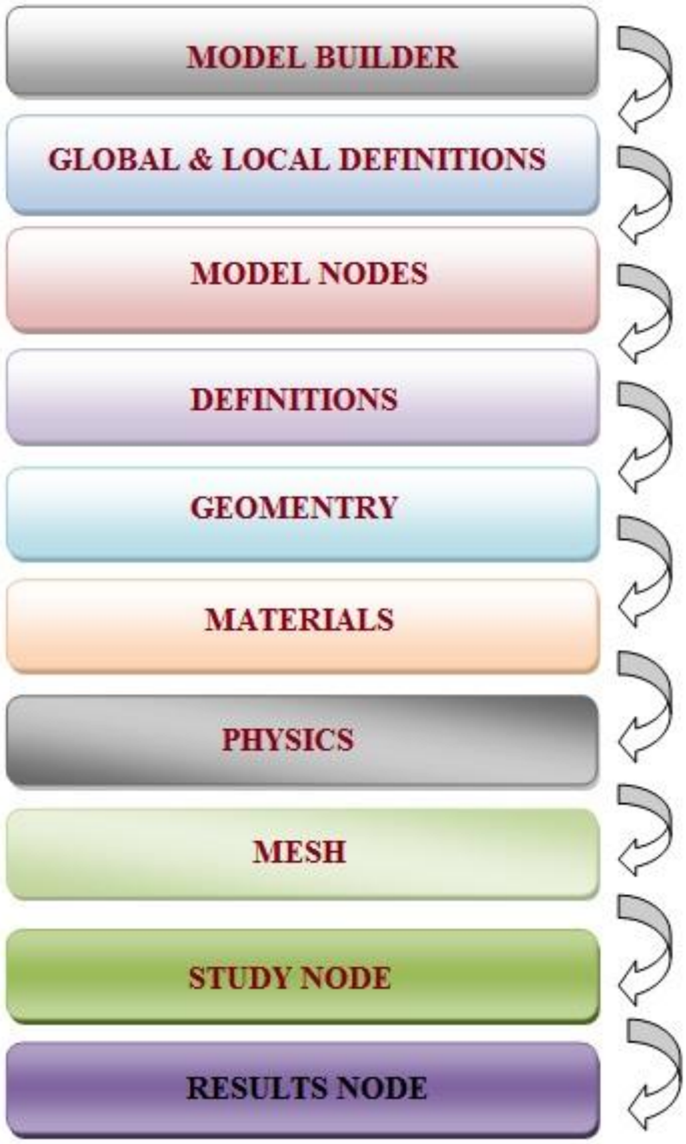

Figure 18: Steps involved in the COMSOL Multiphysics analysis
(COMSOL Inc, 2014)

4.8 Available Glass to cover the solar panel.

The principal intent of the top cover plate used in the solar panels is to protect the solar cells from becoming damaged by the external loads such as aggregation of dust or snow and the cargo due to heavy wind. The solar panel top cover must also be transparent enough to permit the utmost measure of sunlight to go through it, so that the efficiency of the solar cells is not diluted. In lodge to take up sufficiently large loads, while being transparent, tempered glasses are more often than not, used as solar panel top cover (Sunpower, 2013). Tempered glasses are also called as toughened glasses which are physically and thermally stronger than the normal eyeglasses. In typical solar panels that are presently in production, Acrylic glass sheets are also used which are lighter than tempered glass and has physical properties similar to it. In the present study, Acrylic glass material is chosen for the psychoanalysis (Sunpower, 2013).

4.9 Analysis of load carrying capability

The load carrying capability of the selected (**Acrylic)** glass sheet, for the solar panels in the solar roadways application, is investigated using the COMSOL Multiphysics software.

Based on the model of the solar panel for the solar roadways and the standard HS20 loading conditions, the load carrying capability of the Acrylic glass sheets is studied. As the standard length of the truck used in HS20 loading condition is 4.3 m, which is longer than the length of the solar panel modelled for the solar roadways, only one axle weight acts on the solar panels at any given time. Hence the rear axle, where a larger proportion of the weight of the Lorry acts is taken for the analysis. According to the Beer-Lambert law (Jim Clark , 2007) as given in equation 4-1Below, the absorption of the light passing through a material depends on the property of the material and the path length of the light ((Dukhin, A.S. and Goetz, P.J, 2002)) In order to permit maximum brightness to die through the acrylic top cover of the solar panel such that the solar cells receive maximum sun and generate more electricity, the thickness of the top cover is selected as 10mm. The intercourse between the heaviness of the fabric and its light transmission ability is given by

$$\mathrm{I} = \mathrm{I}_{0}e^{-ax} \text{..............................4-1}$$

(Dukhin, A.S. and Goetz, P.J, 2002)

Where **I** is the measured intensity of the light transmitted through a layer of material, $\mathbf{I_0}$The intensity of the light incident on the material, a the absorption coefficient and the thickness of the material. When the HS20 standard truck load is applied to the Acrylic sheet in COMSOL, the effect of the Lorry load on the acrylic sheet is analysed for every 0.1 meters and the load is considered to move in the positive x direction.

The maximum von Mises stress and the maximum displacement based on the location of vehicle rear wheels is given in Table 9.

Table 10: Maximum von Mises stress and displacement of vehicles used for COMSOLanalysis

X position Of Wheel(s) (m)	Lorry (Load due to rear wheels)		Car (Load due to all wheels)		Motorbike (Load due to all wheels)	
	Maximum Von Mises Stress (N/m^2) x 10^9	**Maximum Displacement (m)**	**Maximum Von Mises Stress (N/m^2) x 10^7**	**Maximum Displacement (m)**	**Maximum Von Mises Stress (N/m^2) x 10^7**	**Maximum Displacement (m)**
2.1	0.752	0.0002	4.023	0.0000	0.940	0.0000
2.2	0.986	0.0184	5.280	0.0010	1.740	0.0003
2.3	1.090	0.0614	5.850	0.0033	1.950	0.0011
2.4	1.100	0.1207	5.900	0.0065	1.980	0.0021
2.5	1.270	0.1911	6.790	0.0102	2.305	0.0032
2.6	1.380	0.2694	7.360	0.0144	2.318	0.0044
2.7	1.500	0.3531	8.010	0.0189	2.720	0.0056
2.8	1.570	0.4408	8.420	0.0236	2.885	0.0068
2.9	1.700	0.5313	9.080	0.0285	2.875	0.0080
3	1.640	0.6226	8.750	0.0333	2.982	0.0090

The load locations that results in maximum von Mises stress and displacement as shown in Table 11 are given in the discussion below.

Table 11: Summary of maximum von Mises stress and displacement of various loads Cases analysed in COMSOL

Vehicle type	X position of The front axle (m)	Maximum von Mises stress (N/m^2)	Maximum Displacement (m)
Lorry	3.6	1.82×10^{9}	N/A
	4	N/A	1.1222
Car	5.5	11.7×10^{7}	0.0982
Motorbike	5	6.549×10^{7}	0.0395
Bicycle	2.8	2.06×10^{7}	N/A
	2.7	N/A	0.002

The load caused a maximum von Mises stress of 1.82x103Mpa as shown in Figure 18, is much higher when compared to the ultimate tensile strength of 69Mpa (AKRYLIK Furniture & Accessories, 2014) and the displacement results indicate that maximum surface displacement was also very high at 1.12 meters.

According to the Department for Transport's standards, the allowable deflection for a bridge is span length/800 for vehicular bridges and span length/1000 for pedestrian bridges (Highways Agency, 2013). It may be noted that in the present instance of the top back of the panel, the maximum shift is predicted to be approximately span length/3.6 which is a lot more eminent than the above standard requirements. Hence it can be reasoned that the selected top cover material is not worthy for the applied load and so cannot be applied as a top cover for the solar roadways panel, where vehicles of a size similar to a Lorry.

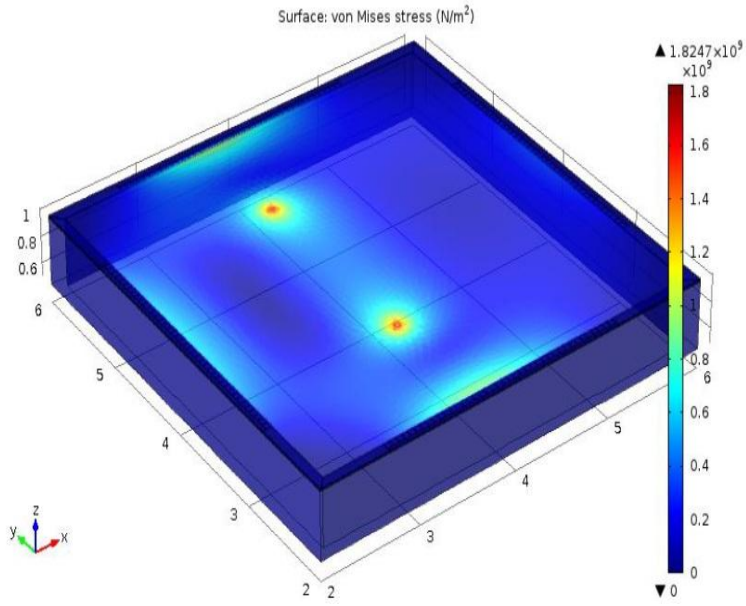

Figure 19: Maximum von Mises stress for HS loading of Lorr on solar panel of the Solar Roadway system (at wheel location of 3.6m)

As the selected material failed for the Load of a Lorry, in the order procedure to examine the maximum load the material chosen for the top cover of the solar roadways panel can bring on, stress and shifts due to a car load and a motorbike load moving over the solar panel are also analysed. The payload of the Mini Copper car and the freight of the Yamaha RZ8 motorbike are selected for the psychoanalysis. The specifications of the selected car and the motorbike are Given in Table 12.

Table 12: Specifications of car and motorbike used in the analysis

	Car (Mini Cooper, 2012)	**Motorbike (YAMAHA FZ8, 2013)**
Weight	616.9 kg (1360 lbs.)	213.2 kg (470 lbs.)
Length	3.05 m	2.1 m
Wheel base	2.04 m	1.5 m
Weight distribution	60/40	51/49

As the wheelbase of the automobile and the motorbike selected for the analysis model smaller than the duration of the solar panel for the solar roadways application, the load due to all four wheels in the sheath of a car and all two wheels in the case of a motorbike are considered for the analysis. The wheelbase of the car selected for analysis is 2.04 meters as shown in Table 12. In this analysis the distance between the front axle and rear axle is held at 2.04 metres, so that only after the front wheels enter and travels a distance of 2.04 meters over the solar panel, the rear wheels enter and move over the solar panel.

The weight distribution between the front and the rear axles confirm to a ratio of 60 to 40

As shown in Table 9. Hence, only 60 percent of the total weight of the car is considered to act on the front wheels and the remaining 40 percent to the rear wheels. The motorbike selected for the analysis has a wheelbase of 1.5 meters. In the analysis, the distance between the front and the rear wheels is maintained at 1.5 meters, so that only after the front wheel enters and travels a distance of 1.5 meters over the solar panels, the rear wheel enters and moves over the solar panels. The weight distribution between the front and the rear wheel are in the ratio 51 to 49, and hence 51 percent of the total weight of the motorbike acts on the front wheel and the remaining 49 percent on the rear wheel.

Based on the selected parameters, the load bearing capacity of the material chosen for the solar roadways solar panel is analysed for the burden of an automobile and motorbike moving over it. The front wheels of the car enter at the x position of 2.1 meters and continue to make a motion in the positive x direction. Later, the front wheels have run through the wheelbase distance of 2.04 meters over the solar panel, the back wheel is considered to 48 enter the solar panel. The maximum von Mises stress and the maximum displacement based on the location of car front wheels is given in Table 11.

As in the previous case, only the load location, that results in the largest stress is presented in the thesis as shown in Table 10 is given in the discussion below.

The burden caused a maximum von Mises stress of 117.48Mpa as shown in Figure 20, which is quite high when compared to the ultimate tensile strength of 69Mpa (AKRYLIK Furniture & Accessories, 2014).

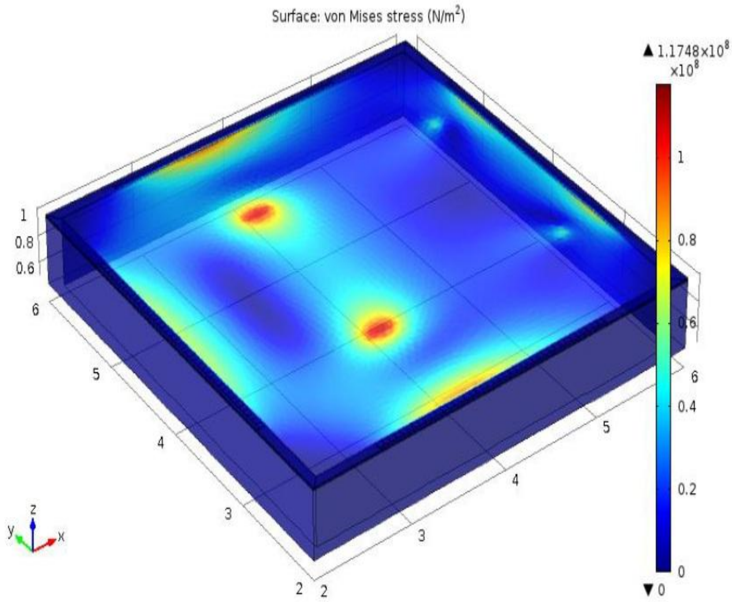

Figure 20: Maximum von Mises stress for load of a car on solar panel of the Solar Roadway system (at front wheel location of 5.5m)

The maximum surface displacement was also found to be very high at 98.19 mm as shown in Figure 21.

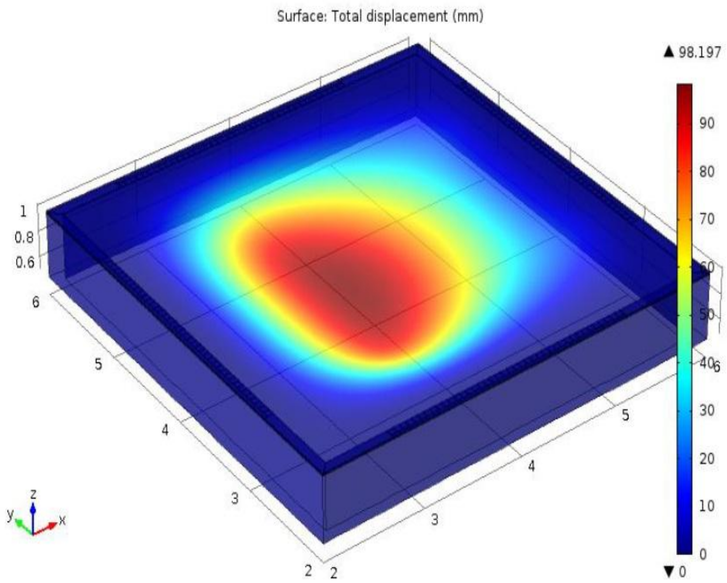

Figure 21: Maximum displacement for load of a car on solar panel of the Solar Roadway system (at front wheel location of 5.5m)

Hence the selected top cover material cannot be used as top cover for the solar roadways panel, when vehicles of a size similar to a Mini Copper car move over the top surface.

Established along the selected parameters, the load bearing capacity of the material chosen for the solar roadways solar panel has been analysed when a load that represents a motorbike move over the control board. The front wheel of the bike enters at the x position of 2.1 meters and goes forward to go in positive x direction. After the front wheel has moved a distance of 1.5 meters over the solar panel, the rear wheel is considered to enter the solar panel. The maximum von Mises stress and the maximum displacement based on the position of the motorbike's front wheel is given in Table 9.

As in the previous case, only the load location, that results in the largest stress is presented in the thesis as shown in Table 10.

It may be noted that the load resulted in a maximum von Mises stress of 65.5Mpa as shown in Figure 22.

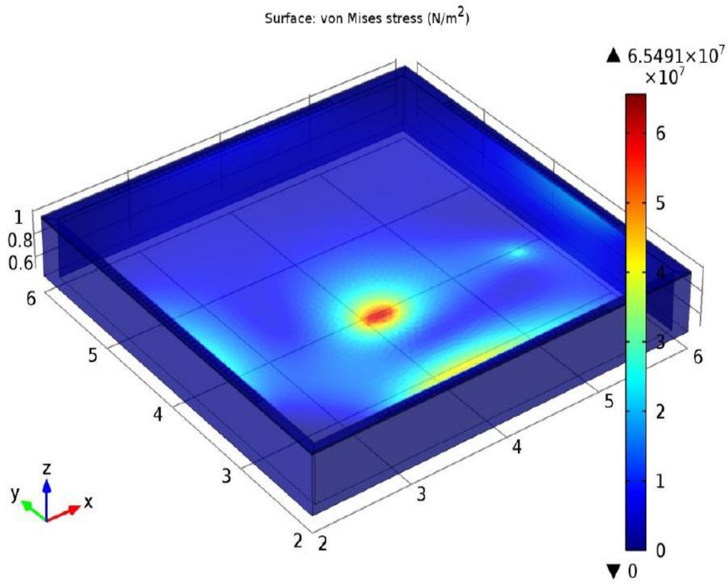

Figure 22: Maximum von Mises stress for load of a motorbike on solar panel of the Solar Roadway system (at front wheel location of 5m)

This value is quite close when compared to the ultimate tensile strength of 69Mpa (Granta Edupack, 2014) and the maximum surface displacement has been found to be quite as high as 39.5 mm as shown in Figure 23.

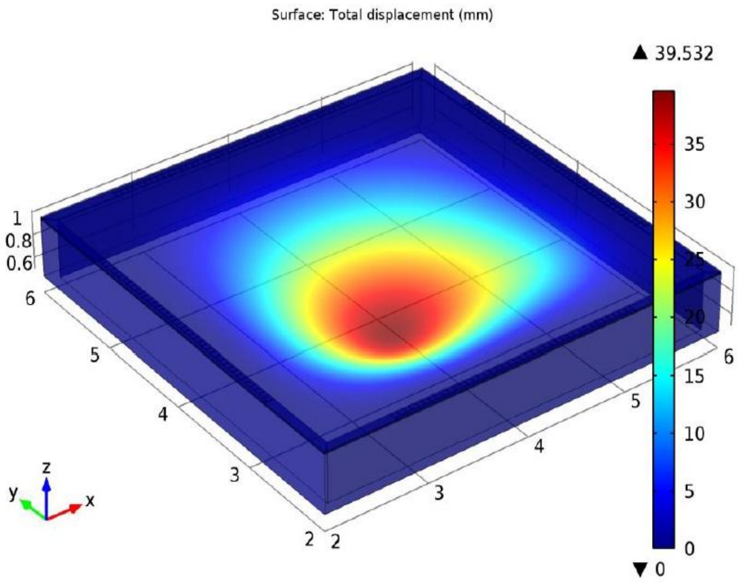

Figure 23. Maximum displacement for load of a motorbike on solar panel of the Solar Roadway system (at front wheel location of 5m)

It is recognised that it is Best to avoid the large deflections in the top cover in order that the vehicle tire rolling up On a slope and as a result, increasing the fuel consumption of the vehicle may be minimised (Brehm, 2012). Established on the predictions, it may be concluded that the selected material cannot be used as top cover for the solar roadways panel, where the vehicles of a size similar to a Yamaha RZ8 (YAMAHA FZ8, 2013) motorbike move over the control board.motorbike move over the panel.

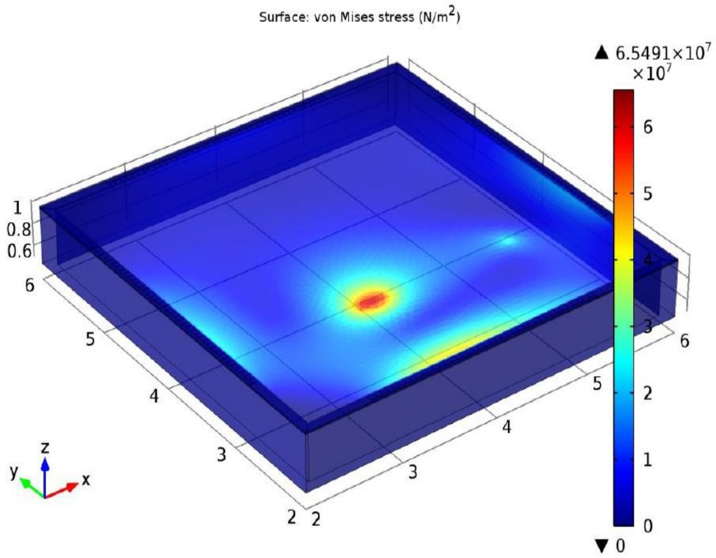

Figure 24: Maximum von Mises stress for load of a motorbike on solar panel of the Solar Roadway system (at front wheel location of 5m)

It may be observed that the diminution in the load induced stress levels and the maximum deflection levels in the selected top cover material may be attained by increasing the thickness of the top screen, while compromising the total sunlight that can pass through it and reach the solar cells. For the increased thickness analysis, 15 mm and 25.4 mm thick plates are selected. Two individual cases of load of a car and of a motorbike going over the solar panel are analysed employing methods discussed earlier.

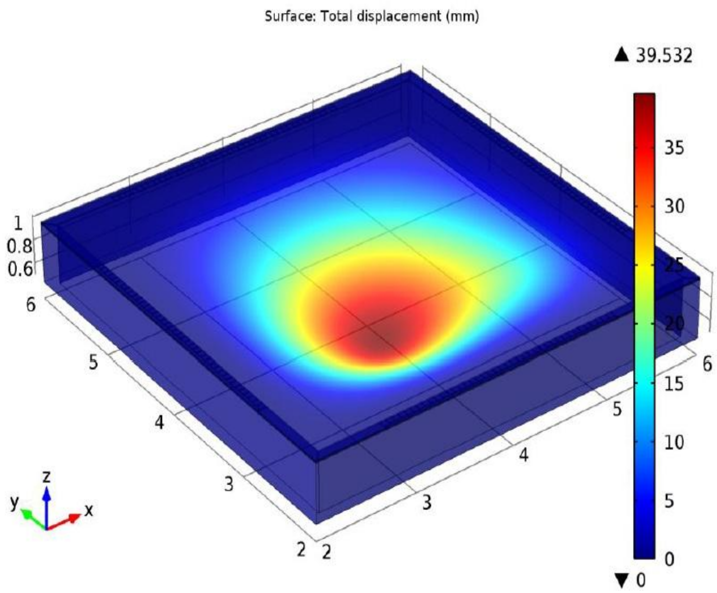

Figure 25: Maximum displacement for load of a motorbike on solar panel of the Solar Roadway system (at front wheel location of 5m)

The increase in the thickness of the material selected for the solar panel top cover shows a drop in the maximum von Mises stress and deflection of the top cover. When the burden of the car is used on the top cover with thickness of 15 mm, the maximum von Mises stress reduced to 52.8Mpa as shown in Figure 26.

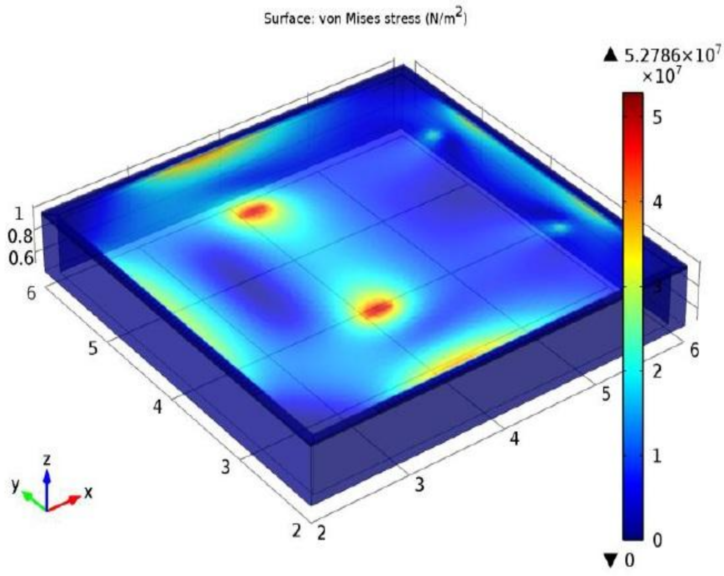

Figure 26: Maximum von Mises stress for load of a car with a top cover thickness 15mm (at front wheel location of 5.5m)

When the burden of the car is used on the top cover with thickness of 15 mm, The maximum deflection of the material has been found to be 29.2 mm As shown in Figure 27.

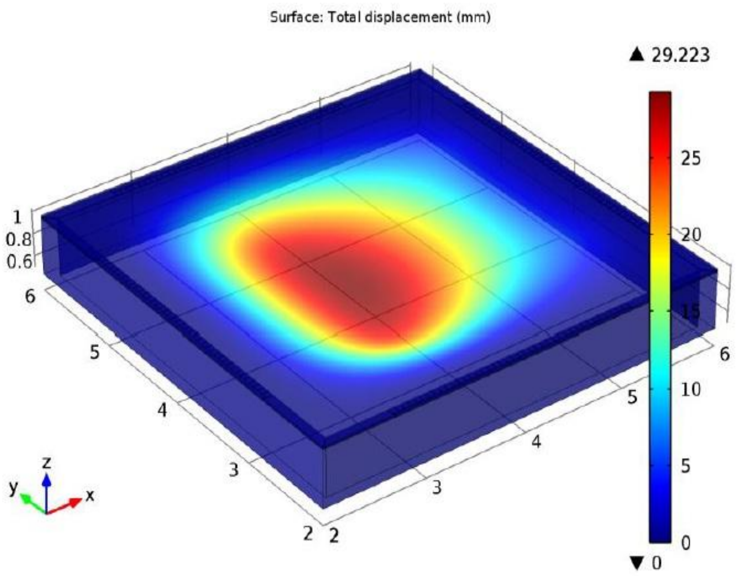

Figure 27: Maximum displacements for a load of a car with a top cover thickness 15 mm (at front wheel location of 5.5m)

When the burden of the car is used on the top cover with thickness of 25.4 mm, the maximum von Mises stress reduced to 18.3Mpa. As shown in the picture, figure 28.

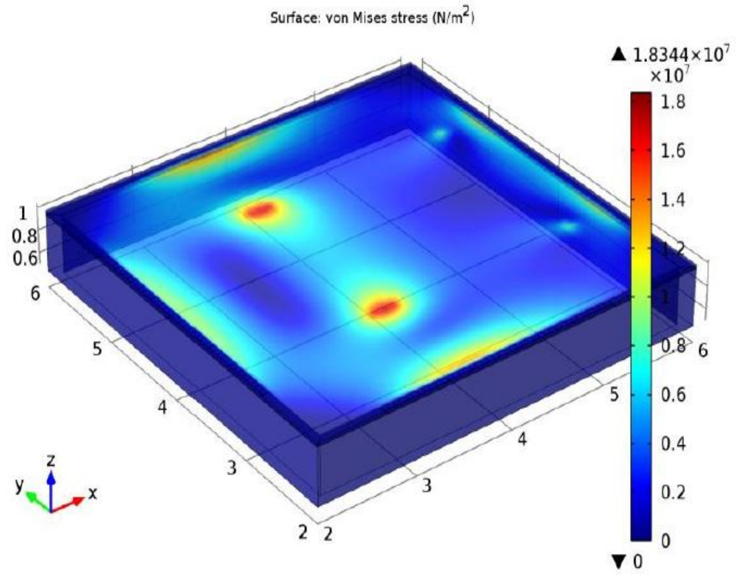

Figure 28: Maximum von Mises stress for load of a car with a top cover thickness 25.4 mm (at front wheel location of 5.5m)

When the burden of the car is used on the top cover with thickness of 25.4 mm, The maximum deflection of the material has been found to be 6.06 mm as shown in Figure 29.

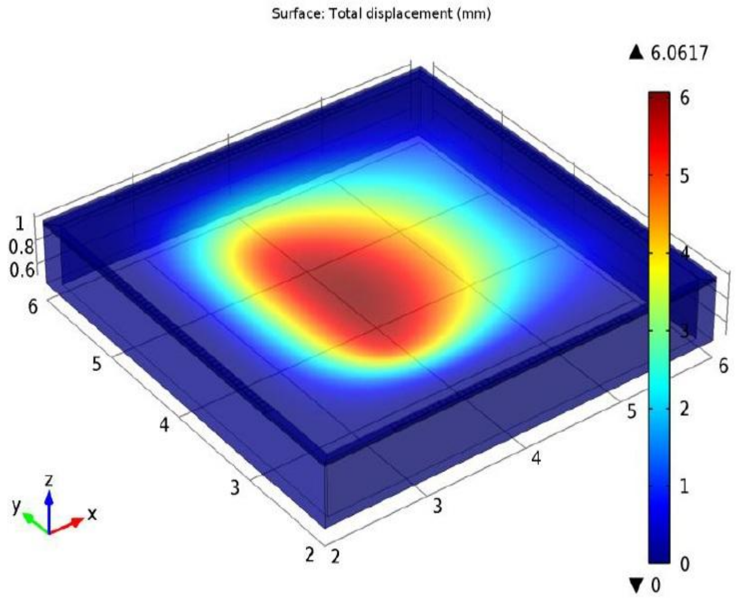

Figure 29: Maximum displacements for load of a car with a top cover thickness 25.4 mm (at front wheel location of 5.5m)

When the burden of the motorbike is used on the top cover with thickness of 15 mm, the maximum von Mises stress reduced to 29.4Mpa as shown in Figure 30.

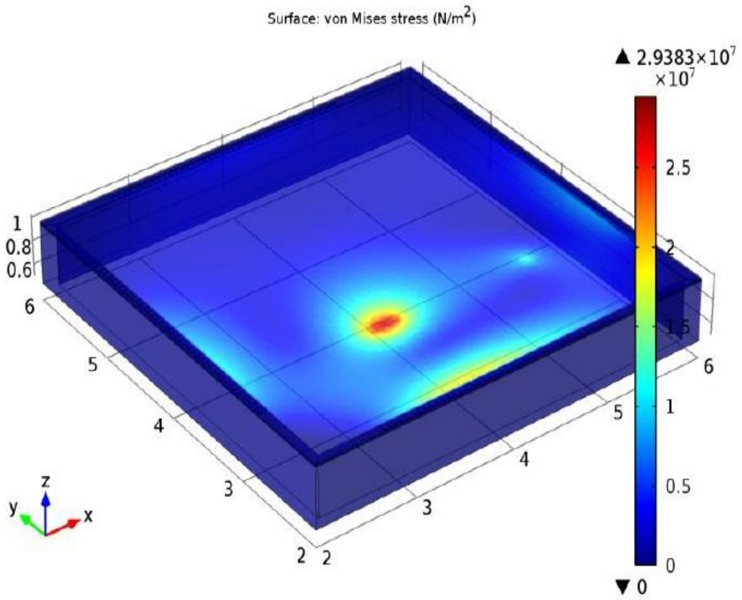

Figure 30: Maximum von Mises stress for load of a motorbike with a top cover thickness 15mm (at front wheel location of 5m)

When the burden of the motorbike is used on the top cover with thickness of 15 mm, the Maximum deflection of the material was 11.7 mm as shown in Figure 31.

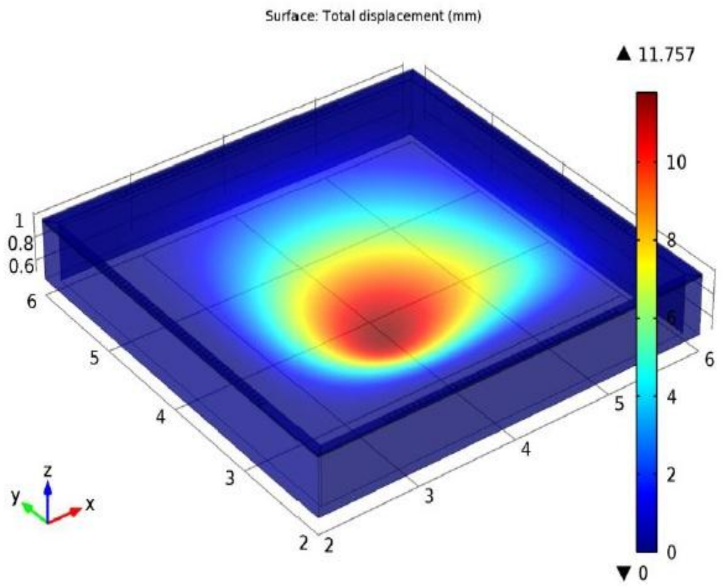

Figure 31: Maximum displacements for load of a motorbike with a top cover thickness 15 mm (at front wheel location of 5m)

When the load of the motorbike is applied on the top cover with thickness of 25.4 mm, the maximum von Mises stress reduced to 10.2Mpa as shown in Figure 31.

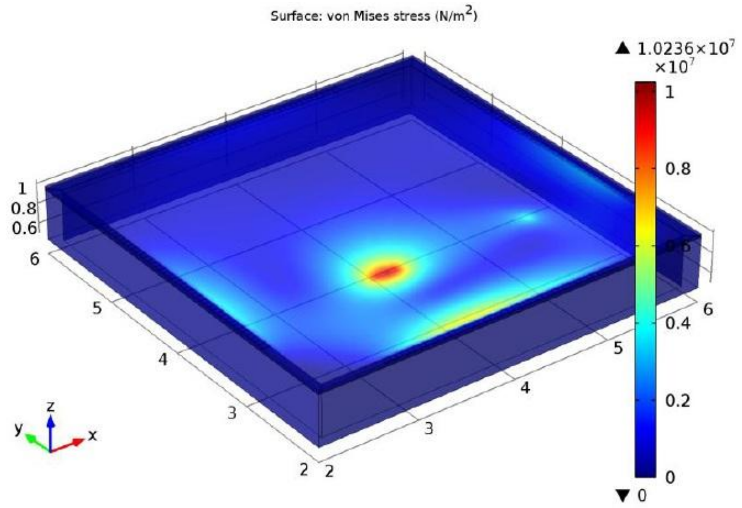

Figure 32: Maximum von Mises stress for load of a motorbike with a top cover thickness 25.4 mm (at front wheel location of 5m)

When the load of the motorbike is applied on the top cover with thickness of 25.4mm the Maximum deflection of the material has been 2.4 mm as shown in Figure 32.

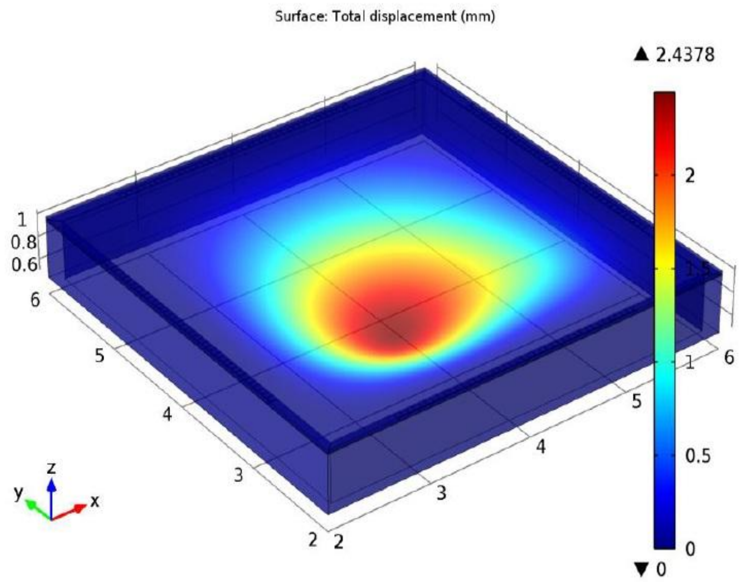

Figure 33: Maximum displacements for load of a motorbike on solar panel with a top cover thickness 25.4 mm (at front wheel location of 5m)

An increase in heaviness of the material from 6 millimetres to 25.4 mm results in reduction of the maximum von Mises stress values at a lower place the ultimate tensile strength, while the maximum deflection remains closer to the Department for Transport standard value. Nevertheless, care must be taken when increasing the thickness since it will cut down the amount of sunlight falling through it.

4.10 Summary

In this chapter, the load bearing capacity of the top cover of the solar panels for the solar roadways application is analysed using COMSOL Multiphysics software. The main motivation for the analysis comes from both material characteristics and solar roadway vehicle applications. The Acrylic plastic material of 10 mm thickness has been picked out for solar panel top cover. It has been shown that this material failed to carry the burden of a typical Lorry, car and motorbike moving over the solar roadway top cover. An addition in the heaviness of the material resulted in an equal decrease in both the deflection and strain in the cloth. Increasing the Young’s modulus also resulted in a reduction deflection and was suitable for accepting the burden of the motorbike and car moving over it. As a currently viable option, solar pathway for a typical bicycle lane was modelled considering the same acrylic plastic as solar panel top cover. This Solar roadway panel was able to hold up the burden of a typical bicycle - person moving over the control board screen.

Chapter 5

Auxiliary Energy Harvesting System to combine with solar roadway

5.1 Introduction

In the solar panels used for the solar roadways application, in accession to the inherent low energy efficiency of the solar panels, losses in the power output due to the shadow effects. Have been found to affect the overall efficiency. In order to overcome these losses in the power output, an auxiliary energy harvesting system employing piezoelectric transducers is proposed. This method relies on converting the strain developed in the solar panel top cover into electricity. In order to increase the efficiency of the auxiliary system, the locations of the piezoelectric elements are optimised using COMSOL Multiphysics by selecting the locations along the outer boundaries of the control board. In particular, among these available edge locations, positions where the high stresses act due to the load of the vehicle over the top cover of the solar panel area of involvement.

5.2 Piezoelectricity

The auxiliary energy harvesting model using piezoelectric materials is suggested. This system analysed using COMSOL Mulitphysics, utilises the stresses developed during the vehicle moving over the solar panel and produce power.

Piezoelectricity is a property exhibited by certain materials such as crystals or ceramics which produce a charge when mechanical stress is given. In piezoelectricity, in generally two types of effects are viewed. The first case is the direct piezoelectric effect, where mechanical stresses due to the external load applied on the piezoelectric material induces displacement in positive and negative lattice elements which themselves induces dipole moments. This results in the establishment of an electric field which applies an electric potential along the electrodes. This event is also called as generator effect (Piezotechnology, 2013). The second case is the reverse or indirect piezoelectric effect, where the piezoelectric material develops a mechanical strength due to the application of an electric sphere. This event is called the motor force (Piezotechnology, 2013). In the present context, the first event, namely the generator effect has been utilised. Piezoelectric devices are used in applications such as sensors, actuators, motors, high power and voltage source and etc. Several materials such as Lead-

Zirconate-Titanate (PZT), Lead-Titanate ($PbTiO_2$), Lead-Zirconate ($PbZrO_3$) and Barium-Titanate ($BaTiO_3$) have been found to exhibit the piezoelectric effect (Piezotechnology, 2013). The relation between the electrical and elastic properties of piezoelectric materials are given by,

$$D + d * T + \varepsilon^T * E \qquad 5\text{-}1$$

$$S = s^E * T + d * E \qquad 5\text{-}2$$

(Piezotechnology, 2013)

Where D represents the dielectric displacement, **T** is mechanical stress, E is the electric field, S is mechanical strain, d is a piezoelectric charge constant, is the permittivity (for T = constant), elastic constant (E = constant) (Phillips, James R.).

In piezoelectric ceramic materials, the ferroelectric domains are lined up by using a DC potential difference across it. The number of domains aligned depends upon voltage, temperature and duration for which the voltage is applied to the material. This process is generally known as poling (Phillips, James R.). Once this process has been successfully performed and when a voltage is applied across the electrodes in the poling direction, the thickness of the piezoelectric material between the electrodes increases and the thickness parallel to the electrodes decreases as shown in Figure 33. Similarly, applying the voltage in the opposite direction will decrease the thickness of piezoelectric material between the electrodes and increase the thickness parallel to the electrodes shown in Figure 33. Applying a compressive force perpendicular to the electrodes or a tensile force in the direction parallel to the electrodes, will generate voltage with a polarity similar to the voltage applied during poling of the material. Similarly a compressive force applied parallel to the electrodes or a tensile force applied perpendicular to the electrodes will result in a voltage generated with polarity opposite to the voltage applied during poling of the material. Applying a shear force to the piezoelectric material will also generate a voltage (Phillips, James R.).

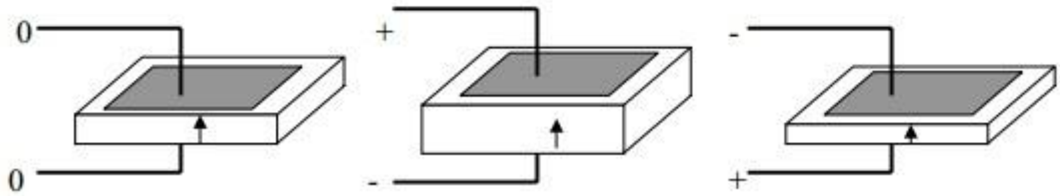

Figure 34: Deformation of piezoelectric elements when voltage is applied in different directions with respect to the poling direction.
(Phillips, James R.)

5.3 Piezoelectric based energy harvesting system for Solar Roadways

In Order to attend into the feasibility of generating auxiliary power, i.e. in addition to the solar power to be generated by Solar Roadways, the use of piezo based energy harvesting system is purported in the present study. It is known that stresses are developed on the top back of the solar panel due to the vehicles moving over it. Using piezoelectric elements these stresses can be harnessed to generate electricity. The electricity generated through this energy harvesting method can partly be used to master the inherent energy losses in the solar panels.

5.4 Piezoelectric elements for solar roadways

For analysing the proposed mechanics and power output of the energy harvesting system for the solar roadways applications COMSOL Multiphysics software is utilised. Lead Zirconate Titanate (PZT-5A) type of piezoelectric material has been chosen for the analysis. As presented in Figure 33.

The dimensions of each piezoelectric element are chosen to be (60mm x 60mm x 10mm), these piezoelectric elements chosen for the COMSOL analysis on the manufacturer's specifications, are recognised to generate 130V DC when a force of 1500N is applied. Typically, the voltages generated are known to vary ± 30%, depending on the layout, stiffness of the plates sandwiching the PZT and etc. based on the info available from the manufacture (Steiner & Martins, 2013).

In the present application these piezoelectric elements are located in between the solar panel top cover and the stem layer. The piezoelectric elements in COMSOL Multiphysics software are generally polarised in the **z** direction, which is then spread out according to the distortion of the piezoelectric elements. The piezoelectric elements are fixed at one end, so that it can limit the piezoelectric elements from any movement due to the load applied to it. The positive and negative terminals are set respectively in the top and bottom of the piezoelectric element. As the vehicles pass over the solar panels, load of the vehicle induces a stress on the piezoelectric elements. This strain induced electricity is utilised in the output power predictions. The maximum principal stress that the selected PZT-5A is subjected to for the bicycle and the motorbike loads, respectively, are 3.14Mpa and 1.4 Mpa (Piezotechnology, 2013)and are lower than the tensile strength of 27.6Mpa (Morgan Advanced Materials, 2009) for the selected material. Hence, the PZT selected material can function under these loads without failure.

5.5 Excellence Piezoelectric placement based on COMSOL Software analysis

Energy harvesting is a process which captures the energy released as waste and changes them into a utilitarian shape. So the energy harvesting process is invariably employed to improve the efficiency of the Solar roadway system. Hence, optimisation of the emplacement of the energy harvesters plays an important part in amending the power production. Piezoelectric elements are employed as an energy harvester to capture the strain and stress, induced voltage caused by the vehicles moving over the solar panels. For exemplar, this energy harvesting method can be a useful mechanism for overcoming the power output losses in the solar panels due to the shadow caused by the vehicles moving over it.

As indicated in Figures 19, 20 and 24 COMSOL Multiphysics analysis of the solar panels in the Solar Roadways application demonstrated compressive stress development in the solar panel top cover as the vehicles move over it. As designated in Figure 26, when the vehicles move over the solar panel top cover, the Load of the vehicles also causes deflection on the top cover. This deflection results in increased tensions along the route of the vehicle on the solar panel top cover and at the homes where the inner boundary of the base layer and the solar panel top cover meet. In order to improve the efficiency of the pizo based energy harvesting process, the piezoelectric elements are located only in the spots where the strain and stresses due to the vehicles moving over solar panel top cover are high. Founded on the

COMSOL Multiphysics analysis, the piezoelectric elements are positioned near the interior borders of the base layer and for a distance of 1.3 metres from the centre crease of the solar panel. The piezoelectric elements are not placed along the outer border of the base layers and at the corners, as the stresses due to the deviation of the solar panels top cover have been found to be relatively low. The piezoelectric element arrangement of the solar roadway solar panels is pictured in Figure 35.

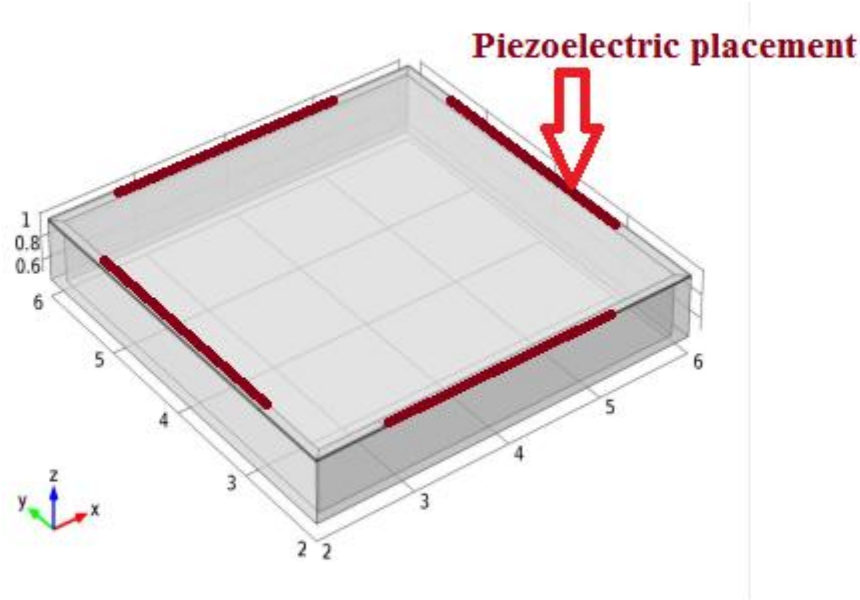

Figure 35: Piezoelectric elements in COMSOL model

5.6 Summary

In this chapter a method using both COMSOL is developed to optimise the position of the piezoelectric elements for use in the auxiliary energy harvesting system for the Solar Roadways. The power output from these piezoelectric elements can be applied to defeat the energy losses in the solar panels of the Solar Roadway system.

Chapter 6

Comparison of the cost of developing one Kilometre Asphalt roadway and Solar Roadway within the UK

6.1 Introduction

The initial price of the solar roadway will be higher than traditional road structure, however the extra benefit of generating clean and renewable energy and being formed of different materials could help this to improve the sustainability aspects of civic infrastructure.

Currently, there are 245 thousand miles 394 thousand kilometres of road in the United Kingdom, according to the Highway Agency Administration, These are largely Motorways, Trunk ‘A’ Road, Principal ‘A’ Road local roads or minor collectors in rural areas of the country which can be generally ignored for the scope of this discussion (Road lengths in Great Britain, 2012) Once hot-mix asphalt (HMA) is paved, it cannot be simply ignored. There are recurring costs associated with the maintenance procedures that are costly and the HMA, it is an increasingly scarce fossil fuel derivative. Also, the bituminous asphalt used in the paving process has to be heated to around 500 degrees, which in and of itself is an absurd waste of energy in such a large scale. On average, these paved roads must be cold paved, or “milled” as the industry calls it, every ten years to be immediately reproved (UK Highway Agency, 2014). One can make the argument that the milled asphalt is recycled, but that would be arguing for a slightly less expensive wasteful system; waste is waste. The prevailing price of HMA has exploded since its inception which is a cause for concern. When taking consideration into account the paving process, the milling process, the maintenance process, the enormous amount of fuel used in all of said aspects, one must come to the conclusion that alternatives will and must be found. And sometimes the best solution seems so obvious: solar roadways. Everyone knows that asphalt is a malleable surface. It can be observed at certain high traffic intersections where the road has deformed due to heavy vehicle stoppage. This is the result of the asphalt absorbing solar energy whereby reconstituting a more malleable state and heavy tires are able to slowly distort the intended surface design. This is the problem that begs the obvious solution. It's possible to harness the energy that is not only being wasted, If the roadway was comprised of photovoltaic panels, not only would there no longer be road distortions, but a sizable amount of energy could be captured for use in myriad needs. This is just one tiny example illustrating the impact solar roadways would have.

6.2 Cost of 1 Kilometre Ashalt roadway

Construction costs per kilometre of road depend on location, terrain, type of construction, number of lanes, lane width, durability, number of bridges, etc. With respect to asphalt, it costs more to build a new road than to rehabilitate a road or add lanes. Roads cost more to build in urban areas than in rural areas. Roads in mountainous terrain are more expensive to build roads than on flat land. Nonetheless, some regions have developed cost models to guide planning for their highway construction programs. These figures show various kinds of highway in the UK.

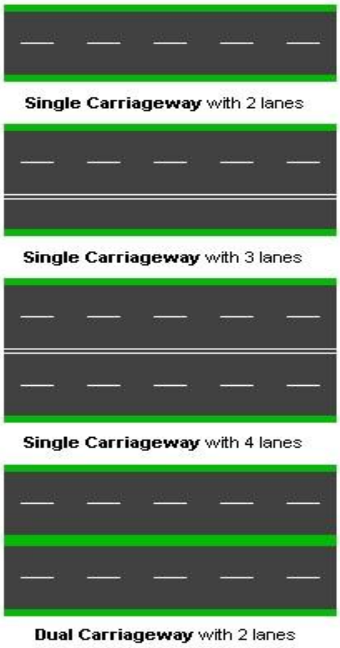

Figure 36: various kinds of highway in the UK.
(UK Highway Agency, 2014)

The average costs of road construction have been quoted. It's well worth it to note that the incremental costs of supply can vary considerably across the network. The table of values for road construction costs that were submitted by the Department of Transport to the House of Commons Select Committee, shown in table 13.

Table 13: Costs of Construction of One Kilometre Asphalt Roadway.

	Number of lanes	Average cost £m/km
Non-Motorways		
Bypass – single Carriageway	2	2.13
Bypass – Dual Carriageway	4	4.54
Dual Carriageway Improvement from Single	2	2.07
Motorways		
New Motorways (3 Lane)	6	6.46
Widening	2	6.16

(Christopher Archer & Stephen Glaister, 2006)

In the UK recent work on estimating road costs has been done by the Department of Transport or the Highways Agency and consultants in their employ. The most recent of these studies was undertaken by EC Harris on behalf of the Highways Agency (EC Harris, 2014). The study, which is yet in progress, seeks to calculate typical construction costs for different road types in rural and urban regions. The data are broken down by road type, then factored for year, location and value using the Highways Agency Road Construction Tender price index. The median monetary value of the schemes is then selected for each road type and hence an average price per km is derived. Footnotes in the analysis suggest reasons for the discrepancies in the results and large deviations from the mean, such as small sample sizes or a high occurrence of major structures in the schemes. Nevertheless, the effects of these structures on cost are not measured.

Furthermore, since the data are split up by road type before analysis, there is no path of examining trends across the various road types, leave out in the final outcome. Dividing the data in such a way will also compound the problem of small sample sizes, increasing the uncertainty of results and leading to possible irregularities such as the cost per kilometre of a rural six lane motorway being £11.5M while an urban six lane motorway at £6.6M as Highways Agency has acknowledged this and are seeking to improve the estimate (UK Highway Agency, 2014).

6.3 Estimates 1 Kilometre Solar roadway.

The targeted cost for a Solar Road Panel is $10,000.00 or £6017. 21 and the lifespan duration for each Road panel is 20 years. The Solar Road Panel standard size is 3.66m by 3.66m (12ft by 12ft), or 13.4 m^2. So based on the generating 4.2kWh average per meter squared (Sunpower, 2013), the Solar Road Panel should average receiving 56.28kWh of energy per day (Solar Roadway.In, 2013).

To work out the monetary value of one kilometre solar roadway, the simple unit conversion has to be Carryout.

1 kilometre = 3,280 Feet

3,280 Feet / 12 Feet = 273 Panel

273 x £6017. 21 = £1.64 Million

Table 14: the average cost of one kilometre solar roadway

Distance of one Lane (Feet)	Solar roadway size (Feet)	Number of Panel (per a Lane)	Solar Road Panel Cost (Thousand/Panel)	Lane Cost (£m/km)
3,280	**12 x 12**	**273**	**£6017.21**	**£1.64**

Table 15: Costs of Construction of One Kilometre Different type of Solar Roadway.

	Number of lanes	Average Cost (£m/km)
Non-Motorways		
Bypass – single Carriageway	2	3.28
Bypass – Dual Carriageway	4	6.56
Dual Carriageway Improvement from Single	2	3.28
Motorways		
New Motorways (3 Lane)	6	9.84
Widening	2	3.28

Table 16: Total Cost to cover whole UK roadways

Lane Cost (£m/km)	Total Roadway Length in the UK (Thousand Km)	Total Cost of the solar roadway in the UK (Million)
£1.64	**394**	**£647,233**

6.4 Summery

The solar roadway alternative could be performed at less cost with an energy return while replacing the old system. As old roads are scheduled to be under maintenance, the process of solar roadway placement could take place. As soon as solar roadways being future-proof, asphalt roads is a dead end. There are no redeeming features to asphalt that should hinder the progress of a new model. The ITS program seems to be begging for a concept that is readily available for the next step. Solar roadways will answer the world problems in the areas of transportation pollution, waste pollution, coal pollution, transportation support, safety, traffic congestion, and energy. As the prevailing cost of a ton of asphalt is continuing upward, photovoltaic cell technology is getting more and more effective. As soon as we can deliver the alternative at £6017. 21 per panel, solar roadways will have surpassed traditional asphalt roads in every arena of debate. At some point, this country will have to come to an action and adopt the solar roadway model of the future.

7.0 Recommendations for future research

Possible extensions to, and expansions upon, the project reported in this thesis are:

- This theory demonstrated the possible use of piezo-based energy harvesting and the prediction of optimal locations.
- For the bearing out of the Solar Roadway system, further research is required in the development of a raw material for the solar panel top cover which can jam on the load and give sufficient grip for the moving vehicles and allow maximum sunlight through to hit the solar cells. The desirable material properties of the Solar Roadways solar panel top cover have been distinguished in this dissertation.

- With the evolution of raw materials for the solar panel top cover, along with the stationary load of the vehicle over the solar panels, response to dynamic loads resulting from the vehicles also has to be analysed using COMSOL. Such as this Report is expected to give more accurate predictions of the load carrying capacity as well as the energy available via the piezo-based energy harvesting system.

- The sustainability benefits of solar road panels should also be looked into. The initial cost of such a panel will be higher than that of a traditional road structure, however the extra benefit of generating clean and renewable energy and being formed of different materials could help this to improve the sustainability aspects of civic infrastructure. One of the challenges of this analysis is defining the lifetime maintenance requirements of such a panel to appropriately determine lifetime costs.

8.0 Reference

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